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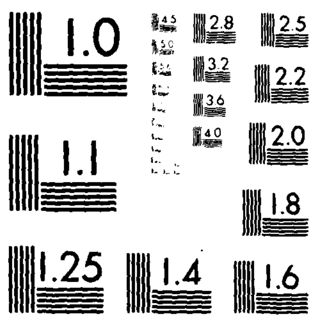

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INTERIM REPORT ON THE CONFLICT MONITORING ANALYSIS OF PARALLEL ROUTE SPACING IN THE HIGH ALTITUDE CONUS AIRSPACE

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JULY 1980

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16. Abstract

The work reported in this document was undertaken as part of the examination of the soundness of the current standards for the spacing between parallel aircraft routes and the enhancement of analytical methods to evaluate future standards. This ~~interim~~ report describes work completed to date on the Conflict Monitoring Parallel Route Spacing Analysis. This analysis assesses the potential for collision and the controller workload associated with aircraft flying on same direction parallel routes. To assess the potential for collision the analysis considers a conflict alert function similar to that employed in the National Airspace System. The conflict alert function detects pairs of aircraft which are projected to violate the radar separation standard within a given time period. In the analysis the event of a conflict alert is followed by a probabilistic delay and a resolution maneuver characterized by a randomly chosen horizontal turn rate. The controller intervention rate is estimated by using a simulation. Actual aircraft tracks were sampled from the FAA data base which supports this activity. These tracks are initiated on the routes based on randomly chosen sector entry times which reflect the level of route loading. For both the potential for collision and the intervention rate, trial results based on a subset of the FAA data are given. Further analysis is required to investigate opposite direction and transitioning traffic. In conjunction with this work, the reliability of the surveillance and control systems has to be addressed as well as other performance measures.

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SUMMARY

This interim report describes work completed to date on the Conflict Monitoring Parallel Route Spacing Analysis. This analysis was performed to assess the potential for collision and the controller workload associated with aircraft flying on same direction parallel routes in the high altitude CONUS airspace with a controller monitoring the aircraft with radar. The analysis has two parts. The first part is an estimation of the potential for collision while the second part is an estimate of the controller intervention rate.

BACKGROUND

In November 1976, the FAA Associate Administrator for Air Traffic and Airway Facilities requested assistance from the Associate Administrator for Engineering and Development in certain analytical activities relating to air traffic separation. In part, that request asked for an examination of the soundness of the current standards for the horizontal separation of aircraft in the continental U.S. The request also called for an enhancement of analytical methods for the operational evaluation of future standards.

The response to that request is a program within the FAA's Office of Systems Engineering Management (AEM-100) to study VOR-defined air route separation. This study's initial goal is to develop an understanding of the relationship of safe route spacing to system performance on the high altitude CONUS en route airways. The system consists of both the airborne and ground elements of navigation and air traffic control. After the safety/performance relationship is better understood, improved specifications of navigation and control system performance needed to support specific route spacings can be developed.

The FAA's VOR-defined air route separation program is based on a data collection followed by analytical activities. Concurrent with the data collection, there are several analyses being performed which address the relationship of navigation and ATC system performance to safety of operations on the VOR route system. These analyses address the potential for collision between aircraft assigned to different routes under various conditions. One analysis addresses the potential for collision between aircraft assigned to parallel routes under the assumption that there is no radar being used to separate the

aircraft. A second analysis addresses the potential for collision of aircraft on intersecting routes where radar is not being used to separate the aircraft. A third analysis, which is described in this paper, addresses the potential for collision and the controller intervention rate for aircraft assigned to same direction parallel routes when the controller monitors aircraft movements with radar surveillance.

The status of the data collection and analytical activities is periodically reported to the Separation Study Review Group (SSRG). This group was formed by the Executive Committee of the Radio Technical Commission for Aeronautics (RTCA) and is charged with reviewing and commenting on the FAA's air route separation program. The membership of the SSRG includes government and industry representatives concerned with navigation issues.

RATIONALE FOR CONSIDERING CONTROLLER MONITORING

In the current system, safety of aircraft which stray beyond the protected airspace boundaries is enhanced by the fact that the minimum allowable spacing between parallel routes is seldom in fact used, that much of the U.S. is covered by a surveillance system in which controllers can and do intervene if potential conflict situations develop, and by the existance of Conflict Alert in much of the system. The FAA rules governing the operation of a pair of routes, as they are currently written, instruct the controller to separate aircraft laterally by clearing them on two parallel routes whose protected airspaces do not overlap. The protected airspace is based on the VOR navigational accuracy of the ensemble of aircraft which operate in the CONUS airspace with no reference either to the existence of a surveillance system or to the traffic density on the routes. Several data collections, including the one performed in connection with this program have confirmed that the protected airspace region associated with a route, in general, contains the aircraft 95% of the time. The implication of this is that in the minimum route spacing configuration, aircraft can be operating in the protected airspace of another aircraft some portion of the flight time. As traffic densities on the route increase, the numbers of operations outside the protected airspace will also increase, if one does not account for the radar monitoring that the controllers use on high altitude routes.

In reality, controllers currently do normally monitor the high altitude CONUS routes. The capability for such monitoring is provided by NAS automation and en route surveillance which is available throughout CONUS for the high altitude route structure. The controller is required to take resolution action

aircraft conflicts detected by the automatic NAS Conflict Alert function. Controller training stresses the anticipation of such conflicts and their resolution before the automatic Conflict Alert is presented. Historical data indicate that the high altitude route structure is safe -- at least there are no records of midair collisions involving aircraft cleared to high altitude parallel routes within the U.S. To date the FAA has not had an analysis tool that would enable it to include consideration of the availability of surveillance and controller intervention in the examination of the various levels of safety associated with different route spacings. The work reported on herein constitutes one of the steps that has been made in that direction.

APPROACH

The measures of performance which are used in this report which relate to the potential for collisions and the workload are the probability of horizontal overlap and the controller intervention rate, respectively.

As the measure of the potential for collision the FAA has expressed an interest in examining the probablity of horizontal overlap. The probability of horizontal overlap is based on a calculation of the chance that aircraft will come very close to one another, due to loss of lateral separation, averaged over a very long interval of flying hours on parallel routes. This calculation is necessarily based on a number of bounding arguments and assumptions as to how the system will behave. These assumptions provide high estimates (i.e, conservative) of the long-term probability of horizontal overlap for systems that are operating under normal (non-failure) conditions and for aircraft that are maintaining their centerline with the accuracy observed on selected routes in the U.S.. Other measures for the potential of collision that reflect system performance in specific situations such as surveillance system outages and situations where aircraft are involved in conflicts due to gross navigation errors will be examined in later phases of this study.

If there is radar surveillance, then an estimate of workload on the controller and the pilot because of the surveillance function is needed. The workload estimator was chosen to be the controller intervention rate. The controller intervention rate was chosen because it is also easily translated into a pilot workload measure, i.e., the number of hours between alerts for a pilot.

THE PROBABILITY OF HORIZONTAL OVERLAP ANALYSIS

As explained above, if the assumption is made that aircraft fly their respective routes independently and the use of radar surveillance is not accounted for, then the estimate of the potential for collision can be high. Since this estimate is dictated by those aircraft which could get near to each other, it is the objective of the Conflict Monitoring Analysis to identify those aircraft which could be affected by controller interventions and to revise the estimate for the probability of horizontal overlap by accounting for collision avoidance maneuvers. It should be noted that the analysis assumes that even with controller intervention there will still be some cases where the conflict detection process may not act in time or the resolution maneuver may be inadequate.

In the current high altitude CONUS airspace, lateral separation is nominally provided by a non-radar procedure even though the aircraft are operating in a radar environment with "radar contact" established. The controller will separate aircraft laterally by clearing them to different routes and when he perceives a potential violation of the radar separation minima he will take corrective action.

When considering the controller's action in separating aircraft, one of the primary issues is the point in time when the controller performs the control action. The time of perception of a conflict will vary from controller to controller. To define this time more explicitly we have chosen to consider the time at which the NAS Conflict Alert would alarm the controller to a potential conflict.

Once a pair of aircraft have the separation and closing speed that would generate a conflict alert there could be a delay before a resolution action is taken. This delay would include:

1. The time due to surveillance errors and tracker lag for the conflict alert function to recognize the potential conflict,

2. The reaction time of the controller to recognize the situation and seize a communication channel, and

3. The time required for the pilot to become congizant of the situation and to initiate the resolution maneuver.

The resolution maneuver is assumed to be a single coordinated horizontal turn by one of the aircraft in conflict. For those

aircraft that are near enough to each other to generate a conflict alert the analysis estimates the probability that the aircraft will collide. This probability of collision is based on the limited resolution scenario adopted for this analysis: a single aircraft executing a horizontal turn after a random delay time. The use of a single horizontal turn by a single aircraft was motivated by the desire to take a very conservative estimate of the effects of controller monitoring. In most potential conflict situations in operational environments, the progress of the conflict would be continuously monitored by the controller and supplementary maneuvers, both vertical and horizontal, could be issued to both aircraft if the initial resolution action was deemed to be ineffective.

Data on the crosstrack deviations and crosstrack velocities of individual aircraft flying selected high altitude routes were used to estimate the joint probability of separation and closing speeds between pairs of aircraft. This joint probability estimate was used in the analysis to indicate the occurrence of potentially conflicting pairs of aircraft. This coupled with the aforementioned delay and resolution maneuver then allowed for a conservative estimation of the probability of horizontal overlap.

THE INTERVENTION RATE ANALYSIS

In order to investigate the rate at which the alerts would be generated a simulation was performed. The simulation used a sample of smoothed radar tracks of aircraft obtained during the FAA's data collection. The entry times of the aircraft were chosen randomly based on the desired traffic loading.

Since the tracks from the FAA's data collection were smoothed to get rid of the radar errors, radar errors had to be added to the track data during the simulation. This was accomplished by choosing a radar site and adding range and azimuth errors to each aircraft position report. The errors that were used were representative of the radar beacon system.

At each radar update time a set of radar returns from every aircraft currently on the routes was processed. This processing included tracking the returns through an emulation of the NAS tracker, and then using the tracker position and velocity estimates in the conflict alert function.

When an aircraft pair received an alert in the simulation, that pair was no longer considered for additional alerts. Furthermore, no attempt is made to realign the tracks of alerted aircraft to account for any response to controller interventions. This means that in the analysis a given aircraft pair can be detected in conflict only once in the sector of

interest. However, the fact that a particular aircraft received an alert with one aircraft did not preclude it from receiving alerts involving other aircraft as it progressed through the sector.

The output from the simulation was an estimate of the number of conflict alerts per sector hour.

TRIAL RESULTS

The analyses previously described were performed with a subset of the lateral pathkeeping performance data collected by the FAA in the Cleveland ARTCC in 1977 and 1978. For the probability of horizontal overlap analysis, data was used that reflected lateral deviations and lateral speeds experienced by aircraft 50 nmi from the VOR. For the controller intervention analysis a randomly selected set of 200 flights were chosen and their entire flight track history in the sectors of interest was used to estimate the frequency of conflict alerts. These data are preliminary in nature, and while the analyses give a good indication of the potential of collision and controller workload associated with a parallel route system, the analyses must be performed with data that reflect pathkeeping performance at greater distances from the VOR and in other ARTCC's. Such data are currently being prepared by the FAA.

At this point in the FAA's VOR-defined air route separation program there is no defined level of the probability of horizontal overlap against which one can compare the results mentioned above. If there were such a level then it would be apparent under what conditions one could demonstrate meeting that level with the assumptions of a procedural environment and under what conditions the conflict monitoring environment would be required.

Even without such a level comparisons might be made between the results from a procedural environment and those from a conflict monitoring environment. If the case could be made that the results from the conflict monitoring analysis were more conservative than those from the procedural analysis, then benefits due to the assumption of a conflict monitoring environment could be made. In this case a particular set of conditions could be adjudged safe in a procedural environment. One could then make the case using the conflict monitoring analysis that under the same conditions with lesser route spacing the system would be just as safe.

In any case, the conservative probability of horizontal overlap estimates produced by the conflict monitoring analysis is far (several orders of magnitude) below the conservative estimates of the probability of horizontal overlap produced by the procedural analysis. These results are shown in Figure 1.

The intervention rate was estimated from the simulation described above. The simulation was replicated ten times, each replication representing different sequences of aircraft which fly through the sector. The results of the simulation for a relatively high traffic loading of five aircraft per hour operating at the same assigned altitude on each of the adjacent routes shows that for an 8 nmi route spacing less than 1 alert per hour would be expected. The results of the intervention rate simulation are shown in Figure 2.

FUTURE WORK

This paper addresses an analysis applied to one scenario (i.e., same direction, nontransitioning parallel routes) using one set of data at a specified distance from the VOR. Further work in this area requires a sensitivity analysis which should investigate the use of other data sets and other input parameters. The sensitivity analysis should also investigate certain of the analytical assumptions. This should be followed by an augmentation of the analysis to investigate opposite direction and transitioning traffic. If surveillance is shown to be required to handle the traffic load, then the reliability of the surveillance system and control system will need to be addressed as well. The methodology used in the Conflict Monitoring Analysis addresses the average probability of horizontal overlap. In order to develop a better understanding of the safety of the system other measures which address the potential for collision in specific situations such as the system performance against a worst case blundering aircraft will also have to be examined.

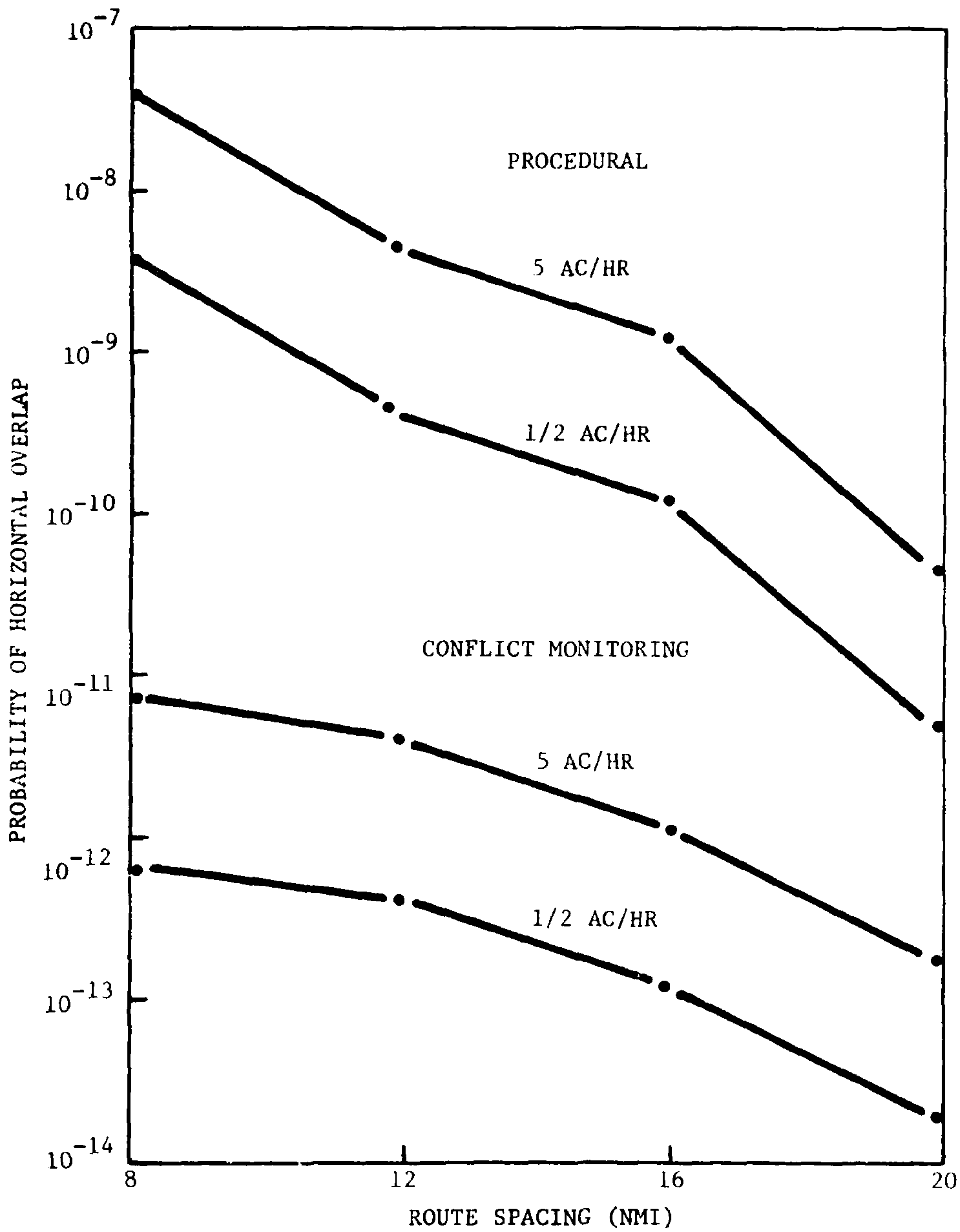

FIGURE 1
TRIAL PROBABILITY OF HORIZONTAL OVERLAP ESTIMATES AS A FUNCTION OF ROUTE SPACING

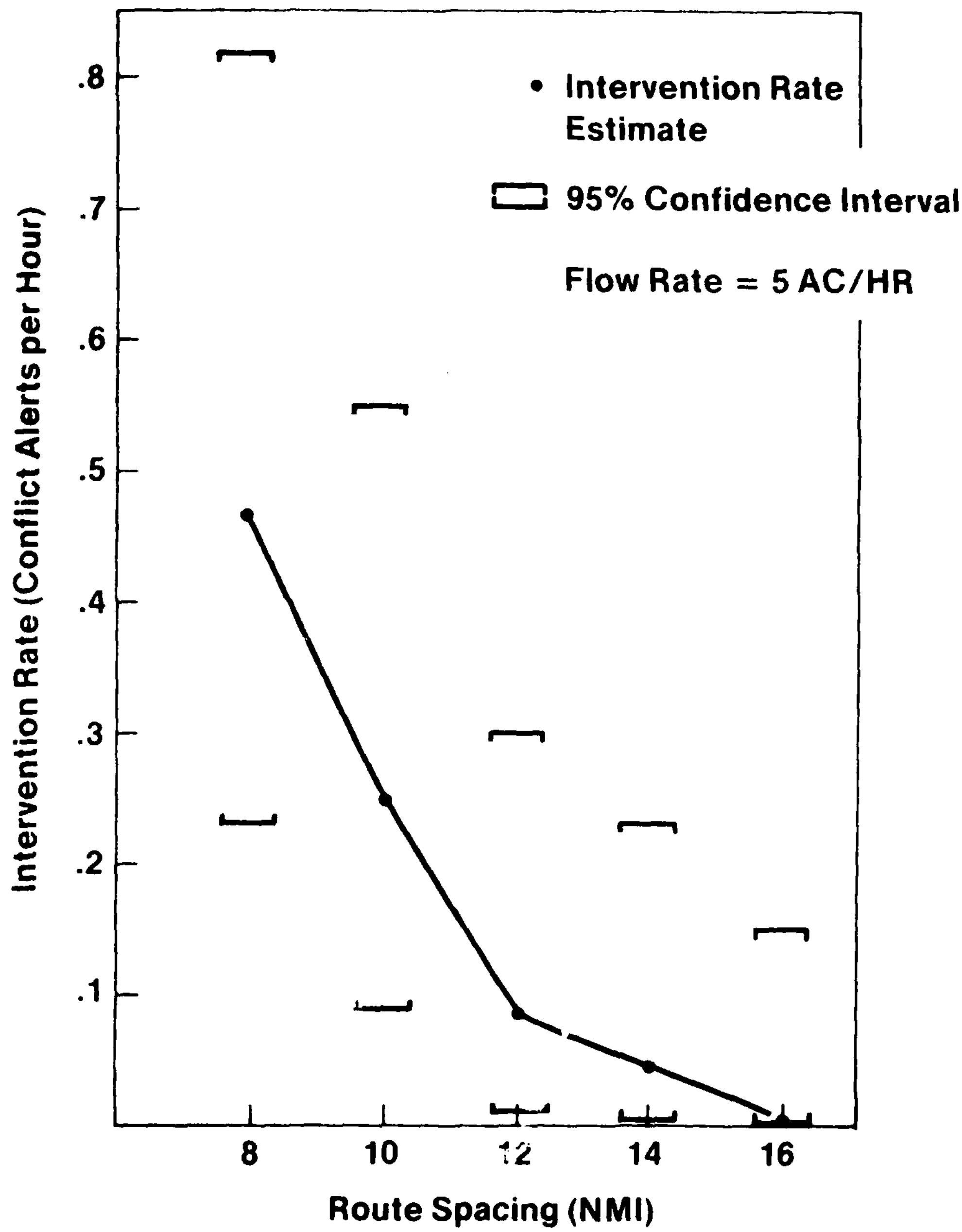

FIGURE 2
INTERVENTION RATE
RESULTS FROM SIMULATION

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1. INTRODUCTION

1.1 Background

In November 1976, the FAA Associate Administrator for Air Traffic and Airway Facilities requested assistance from the Associate Administrator for Engineering and Development in certain analytical activities relating to air traffic separation.(1) In part, that request asked for an examination of the soundness of the current standards for the horizontal separation of aircraft in the continental U.S.. The request also called for an enhancement of analytical methods for the operational evaluation of future standards.

The response to that request is a program within the FAA's Office of Systems Engineering Management (AEM-100) to study VOR-defined air route separation. This study's initial goal is to develop an understanding of the relationship of safe route spacing to system performance on the high altitude CONUS en route airways. The system consists of both the airborne and ground elements of navigation and air traffic control. After the safety/performance relationship is better understood, improved specifications of navigation and control system performance needed to support specific route spacings can be developed.

The FAA's VOR-defined air route separation program is based on a data collection followed by modelling and analytical activities. The precursor to the data collection was a mini data collection in 1975 done by MITRE with support from ANA-220 at NAFEC.(2) From this experience, MITRE wrote the specifications for the main data collection.(2,3) The main data collection was planned and conducted by NAFEC (ANA-220) from September 1977 to April 1978.(4) At the present time, NAFEC is reducing the data and compiling the data base.

Concurrent with the data collection, there are several analyses being performed which address the relationship of navigation and ATC system performance to safety of operations on the VOR route system. These analyses address the potential for collision between aircraft assigned to different routes under various conditions. NAFEC's analysis addresses the potential for collision between aircraft assigned to parallel routes under the assumption that there is no radar being used to separate the aircraft.(5) There is also an effort at Princeton University to address the potential for collision of aircraft on intersecting routes where no radar coverage is available.(6)

MITRE's analysis, which will be described in this paper, addresses the potential for collision and the controller intervention rate for aircraft assigned to same direction parallel routes when the controller monitors aircraft movements with radar surveillance. The future tasks which MITRE will do will include a sensitivity analysis of the parameters used in its analysis. This will be followed by an investigation of opposite direction and transitioning traffic. If surveillance is shown to be required to handle the traffic load, then the reliability of the radar and control system will need to be addressed as well. The methodology used in the MITRE model addresses the average probability of horizontal overlap. In order to develcp a better understanding of the safety of the system other measures will also have to be examined which address the potential for collision in specific situations.

The status of the data collection and analytical activities are periodically reported to the Separation Study Review Group (SSRG). This group was formed by the Executive Committee of the Radio Technical Commission for Aeronautics (RTCA) and is charged with reviewing and commenting on the FAA's air route separation program.(7) The membership of the SSRG includes government and industry representives concerned with navigation issues.

1.2 The Rationale for Examining Route Spacing in a Surveillance Environment

The FAA initiated the route spacing analytical task in a surveillance environment to ensure that all factors contributing to the safety of the route structure were being assessed. The rules governing the route structure, as they are currently written, instruct the controller to separate aircraft laterally by clearing them to two routes whose protected airspace do not overlap. The protected airspace is based on the VOR navigational accuracy of the ensemble of aircraft which operate in the CONUS airspace with no reference to the existence of a surveillance system. The attractive feature of this criterion is that it can be applied universally for designing routes and the failure of the surveillance system need not be an issue in the design. To require the presence of a surveillance system for a given route spacing and traffic loading would be a departure from the current FAA requirements concerning the use of surveillance.

However, under the charter to examine the current standards, the present task must examine the effects of procedural control on the route spacings with the current traffic loading on the

routes. If one were to assume that radar is not used to provide lateral separation in the current system then one could use a procedural control analysis. In such an analysis, it is assumed that aircraft on adjacent routes operate independently. This assumption of independence will give a higher estimate for the potential for collision than the potential for collision truly experienced by the system. The reason for this is that those aircraft which have significant deviations from their assigned routes have a chance to collide with aircraft flying independently on the adjacent route. In reality, if two aircraft are observed via radar by the controller to be on a collision course, resolution commands would be issued and this would reduce the possibility of collision.

Historical data indicate that the high altitude parallel route structure is safe -- at least there are no records of midair collisions involving aircraft cleared to high altitude parallel routes within the U.S.[8] However, if by analyzing the current system as if it were a strictly procedural system produces an estimate of the potential for collision for the current parallel route spacings that does not demonstrate consistency with the historical record, then the assumptions of the analysis have to be questioned. There might be several reasons why the procedural analysis could overestimate the potential for collision. For instance, one explanation would be that the routes are really loaded with traffic in a dependent manner rather than in the independent manner assumed by the procedural control analysis. However, there is no evidence from the FAA's data collection to suggest that the parallel routes were not loaded independently.

A more likely explanation for the overestimate would be that radar is used to provide separation in the current system. The estimates for the potential for collision in the procedural analysis result from the aircraft that exhibit large crosstrack deviations. In the current system it is very likely that the controller will direct changes in the course of aircraft that exhibit large deviations -- particularly if there is a nearby aircraft on the adjacent route. Therefore, this paper will describe an analysis which reflects the current system's ability and requirement to monitor and resolve potential conflicts.

1.3 Objective

The purpose of this report is to describe the Conflict Monitoring Analysis. The analysis has two parts. The first part is an analysis to estimate the potential for collision in a surveillance environment while the second part is an analysis to estimate the controller intervention rate. This description

will be followed by initial trial results based on U.S. data from the Cleveland ARTCC.

1.4 Route Spacing Environment

The environment being considered here is the high altitude (above 24,000 feet) CONUS airspace. More specifically, only same direction parallel routes having no transitioning traffic are considered. It is also assumed that there is complete radar coverage and the mechanism which will limit collisions in this system is Conflict Alert. The Conflict Alert function in this analysis is used as a bound on the actual behavior of the system. It is assumed that in most cases, the controller will detect potential conflicts in advance of the Conflict Alert alarm and thus have more time to resolve the potential conflict.

1.5 System Performance Measures

Measures of performance that relate to the potential for collision and the workload associated with the controller intervening with aircraft are used in the Conflict Monitoring Analysis.

1.5.1 Workload Measures

If there is radar surveillance, then an estimate of workload on the controller and the pilot because of the surveillance function is needed. The workload estimator was chosen to be the controller intervention rate. The controller intervention rate was chosen because it is easily translated into a pilot workload measure, the number of hours between alerts for a pilot. It is also a measure that is directly related to the function of conflict alert.

1.5.2 Safety Measures

Developing an estimate for the potential of a collision is done to give the ATC decision maker information about the system. Safety is a value judgment made by the ATC authority that must necessarily be based on a number of factors that are obtained from outside the analysis as well as quantitative estimates derived from the analysis. "Safety" may be defined as the quality of assuring freedom from harm, injury, or danger. The quantitative values that partially determine the safety judgment may be referred to as "risk", defined as the probability of occurrence of a specified loss or hazard. In the route spacing context safety judgments are based on an assessment of the potential for collision between aircraft assigned to adjacent

routes. The risk measure selected by the FAA is the probability of horizontal overlap. In this paper, the risk measure is based on a calculation of the probability that a certain set of aircraft will come very close to one another in the horizontal dimension when the aircraft were planned to have a nominal crosstrack separation. This calculation is necessarily based on a number of bounding arguments and assumptions as to how the system will behave. These assumptions provide upper bounds on the long-term probability of horizontal overlap for systems that are operating under normal (nonfailure) conditions and for aircraft that are maintaining their centerline with the accuracy observed on selected routes in the U.S.. The safety associated with the route spacing system must therefore be assessed not only on the basis of this analysis but also on the basis of other attributes. These attributes include the frequency of and the risk associated with periods of navigation system or ATC system failure, the frequency of and risk associated with periods of well above average traffic loads on parallel routes, and the risk associated with specific aircraft blunder situations involving rapid unanticipated turns toward aircraft or an adjacent parallel route.

2. OVERVIEW OF THE METHODOLOGY

The minimum route spacing in the U.S. is based on the extent of Federal airways(9). The extent of a Federal airway defined this context as protected airspace is described to be an area within 4.5 degrees of the route centerline at a distance greater than 51 nmi from the route-defining VOR. At a distance less than 51 nmi from the VOR the protected airspace is defined to be within 4 nmi of the route centerline. Several data collections, including the one performed in connection with this program, have confirmed that this region in general contains the aircraft 95% of the time. The controller is told that lateral separation between two aircraft is sufficient if the aircraft are cleared on two routes whose protected airspace does not overlap. There is no requirement for radar surveillance to be available for the controller to make such clearances.

One can infer from the current criteria that for VOR's spaced less than 102 nmi apart, the centerlines of two parallel routes could be 8 nmi apart. Based on the controller's handbook,(10) an aircraft could be cleared to fly one of these routes without radar surveillance and without regard to the traffic on the other routes. The implication of this is that in the minimum spacing configuration aircraft can be operating in the protected airspace of another aircraft some portion of the flight time. As traffic densities on the route increase, the numbers of operations outside the protected airspace will also increase.

The historical evidence shows that there has not been a midair collision between aircraft on parallel routes in the high altitude CONUS airspace.(8) Two factors not considered in the basis for route spacing criteria may contribute to this accident free record. The first is that there is virtually complete radar coverage of the high altitude CONUS routes. The second factor is that almost all routes in the CONUS high altitude airspace that can be considered to be even approximately parallel are spaced more than 8 nmi apart. There could conceivably be other factors that have contributed to the safety of the U.S. high altitude airspace. One such factor might be a systematic loading of the routes to reduce the proximity of aircraft on adjacent routes. However, during the FAA data collection there was no evidence that routes were being loaded in a dependent fashion. Each route from the standpoint of clearances was operated independently. Therefore, as pointed out in the previous section, if the system analyzed with the procedural assumptions indicates there is a high potential for collision, then the role of surveillance should be investigated in order to make the estimated potential for collision agree more closely with the observed safety record.

2.1 Formulation of the Analysis for Parallel Routes in a Procedural Environment

In a procedural environment the controllers clear aircraft onto parallel routes in a certain manner and thereafter the aircraft are considered to be separated. When the controller clears an aircraft onto a route he considers the aircraft to be separated vertically from another aircraft if the two aircraft are assigned to different flight levels. The aircraft are separated laterally if the protected airspace of their assigned routes do not overlap. The aircraft are separated longitudinally in a procedural environment by time or, if DME equipped, by distance. As long as the clearance separates aircraft in at least one dimension, the aircraft are considered to be separated. The analysis here will only consider the risk of collision due to the loss of the planned lateral separation of the aircraft.

In analyzing the procedural environment no further control is assumed beyond the planned separation contained in the clearance. More specific assumptions which are usually made in analyzing a procedural environment are the following:

1. There are no collision avoidance maneuvers or ATC-aircraft communications which would instigate a collision avoidance maneuver. The effect of such an assumption is conservative (i.e., the analysis would produce a high estimate risk that aircraft would come close together) if one believes that more times than not a collision avoidance maneuver is generally effective in preventing a collision.

2. ATC makes no errors which would increase the probability of collision in the assignment of aircraft to routes. The basic purpose of the analysis is to estimate the potential for aircraft coming close to one another due to loss of planned lateral separation. For example, if the controller had assigned an aircraft to the wrong route by giving the wrong clearance then this error has nothing to do with the spacing between the routes and should not be considered.

3. Only one pair of parallel routes is considered. More specifically the aircraft on these routes are assumed to be flying in the same direction without changing their flight level.

4. The entry of aircraft onto one route is assumed to be independent of the entry of aircraft onto the other route.

5. The flying errors for an aircraft in the alongtrack, the crosstrack, and the vertical dimensions are assumed to be independent.

6. The flying errors between neighboring aircraft are independent. In general there are conditions such as weather which might tend to cause correlated errors. Since the resulting flying errors are usually correlated in the same direction, the true potential for aircraft coming close together would probably be less than that estimated by the analysis.

7. The flying errors are assumed to be time-invariant. This means that a sample of flying errors taken at a specific distance from the VOR over all weather conditions is assumed to have the same distribution as another such sample taken at a later time. This assumption allows an estimate to be made over long periods of time.

To perform the analysis in a procedural envionment, further assumptions are required to make the mathematics tractable. These assumptions are that only two aircraft enter into a horizontal overlap simultaneously, only nearby aircraft contribute to the potential of the overlap, the aircraft shape is a rectangular parallelepiped, and that the aircraft do not pitch, bank, or yaw.

To estimate the probability of horizontal overlap in the procedural environment we will use the assumption that the flying errors in each dimension are independent. Thus, if we define P_x to be the probability that the aircraft shapes overlap in the alongtrack dimension and P_y to be the probability of overlap in the crosstrack dimension then the probability of horizontal overlap is P_xP_y. The estimate of P_x will depend on the traffic density on the routes and the speed and size of the aircraft. A model for producing an estimate of P_x can be found in Appendix E of Volume II of this report. The estimate for P_y will depend on the crosstrack navigational performance of the aircraft and the aircraft size. The data taken for this program are used to determine the single aircraft crosstrack deviations from centerline. By convolving two such distributions one arrives at the distribution of the separation between the aircraft. The estimate of P_y is made by computing the probability that the aircraft pair will be separated by less than a wingspan.

2.2 Adaptation of the Methodology to a Conflict Monitoring Environment

The surveillance environment which is being investigated is the CONUS en route high altitude airspace. In this airspace the controller will clear aircraft onto routes in such a way so as not to lose the radar separation with the aircraft immediately in front of it on the same route for at least the period of time when both aircraft are in the same sector. Adjacent routes are far enough apart so that by clearing aircraft on two separate routes the aircraft can be nominally considered to be laterally separated. However, the controller will be able to observe the progress of the aircraft along the route. If it appears that the aircraft will violate the radar separation standard, then the controller can intervene with one or both of the aircraft and try to resolve the conflict.

For a system with controller interventions, the first procedural assumption which is not applicable is that no collision avoidance maneuvers are used. ATC initiated collision avoidance maneuvers will be considered in the conflict monitoring model. To be conservative, the only collision avoidance maneuvers which will be considered are those that are generated by the controller.

With collision avoidance maneuvers assumed, it is now necessary to consider that aircraft in close proximity are nonindependent pairs. In the procedural analysis, independence was assumed between all aircraft so that their flying errors could be thought of in terms of single aircraft statistics. In the surveillance environment controller intervention occurs based on aircraft position and velocity relative to other aircraft. Thus, pairs of aircraft which are in potential conflict are no longer allowed to fly independently.

It is still assumed that aircraft enter their respective routes independently and they operate independently until the controller intervenes. Once the controller intervenes, we will be interested in the horizontal separation between the aircraft pair as a conflict resolution maneuver is executed. In the horizontal plane, we will be concerned with the overlap of the collision shapes but not the angle at which they enter into overlap. The natural collision shape in this situation is the right cylinder. The remainder of the procedural assumptions will carry over in the surveillance analysis, including the assumption of the time-invariant nature of the flying errors.

In the surveillance environment we will be interested in estimating the probability of horizontal overlap, P_H. The next section of this report will describe how P_H is estimated.

3. DESCRIPTION OF THE CONFLICT MONITORING HORIZONTAL OVERLAP ANALYSIS

The purpose of the Conflict Monitoring Horizontal Overlap Analysis is to estimate the probability of horizontal overlap when there is a controller monitoring the air routes using radar surveillance. As explained previously, if the assumption is made that aircraft fly their respective routes independently and the use of radar surveillance is not accounted for then the probability of horizontal overlap will be high. Since the probability of horizontal overlap is dictated by those aircraft which could get near to each other, it is the objective of the Conflict Monitoring Analysis to identify those aircraft which could be affected by controller interventions and to revise the estimate for the probability of horizontal overlap by accounting for collision avoidance maneuvers. It should be noted that the analysis assumes that even with controller intervention there will still be some cases where the conflict detection process may not act in time or the resolution maneuver may be inadequate.

This section will describe the estimation of the value of the probability of horizontal overlap, P_H. The process through which this variable is estimated is shown in Figure 3-1. Each step in the process is identified with the section in which it is discussed. The probability of horizontal overlap depends on the probability of being separated alongtrack, the total delay, the resolution maneuver, and the probability of being near to the conflict boundary. The input to this process is provided by the system specifications, auxillary analysis, and data as shown in the top row of boxes in Figure 3-1.

3.1 Conflict Scenario

In the current high altitude CONUS airspace, lateral separation is nominally provided by a nonradar procedure even though the aircraft are operating in a radar environment with "radar contact" established. The controller will separate aircraft laterally by clearing them to different routes and when he perceives a potential violation of the radar separation minima he will apply radar separation.

When considering the controller's action in separating aircraft, one of the primary issues is at what point in time does the controller perform the control action. The time of perception of a conflict will vary from controller to controller. To define this time more explicitly we have chosen to consider the time at which the NAS Conflict Alert would alarm the controller to a potential conflict.

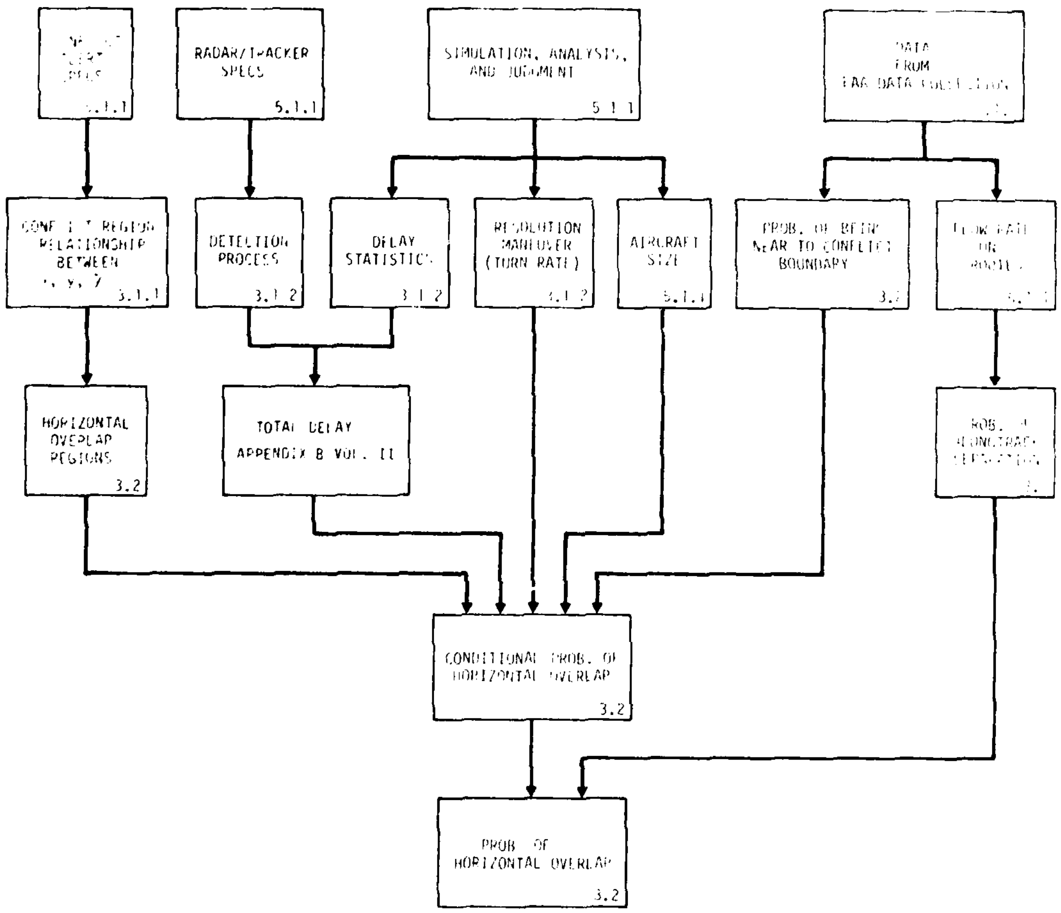


FIGURE 3-1
CONFLICT MONITORING
HORIZONTAL OVERLAP ANALYSIS

The controller, in providing separation between aircraft, is expected to anticipate the situation (i.e., to look ahead farther in time than the automated Conflict Alert) and take steps to resolve a potential conflict before a Conflict Alert is displayed. Therefore, if the NAS Conflict Alert is properly designed it would tend to alarm at a time later than the controller would normally perceive the conflict and provide for its resolution. Given that the controller would normally perceive a potential conflict with more lead time than is provided by Conflict Alert, it follows that the controller-initiated action should result in less of a risk of collision than a later Conflict Alert-initiated maneuver. If the NAS Conflict Alert is available, then the perception of a potential conflict will be no later than the automatic alarm and the risk of collision will be no greater than that due to initiating a resolution action at the time of the automatic conflict alert. Therefore, the NAS Conflict Alert function will be used in the analysis as a conservative indicator of the time that a potential conflict is perceived by the controller.

3.1.1 The Conflict Region Boundary

To analyze the NAS Conflict Alert function we need to have a mathematically tractable way of describing when an aircraft pair would be detected to be in potential conflict and when it would not. Basically, the way that the NAS Conflict Alert works is that pairs of aircraft are subjected to a set of coarse positional and velocity filters. Passing these coarse filters indicates that the pair is near to each other and generally closing. The aircraft pairs that pass the coarse filtering are then subjected to a set of fine filters. These fine filters project the positions of the pair ahead in time. If, within a given look-ahead time, the pair is projected to be separated by less than a certain distance, then the pair is considered to be in potential conflict. If the pair passes the filters two out of the last three times the filters are applied then the controller is alerted to this conflict pair by the NAS automation blinking the aircraft symbology on his screen.

The NAS Conflict Alert projects the aircraft positions in three dimensions and uses different factors in each filter depending on how many times a pair has consecutively passed the filter. Appendix H of Volume II of this report gives a more detailed description of the NAS Conflict Alert. In this analysis of the NAS Conflict Alert we will only consider the horizontal component of Conflict Alert because we are addressing only coaltitude aircraft. Also we will declare a potential conflict

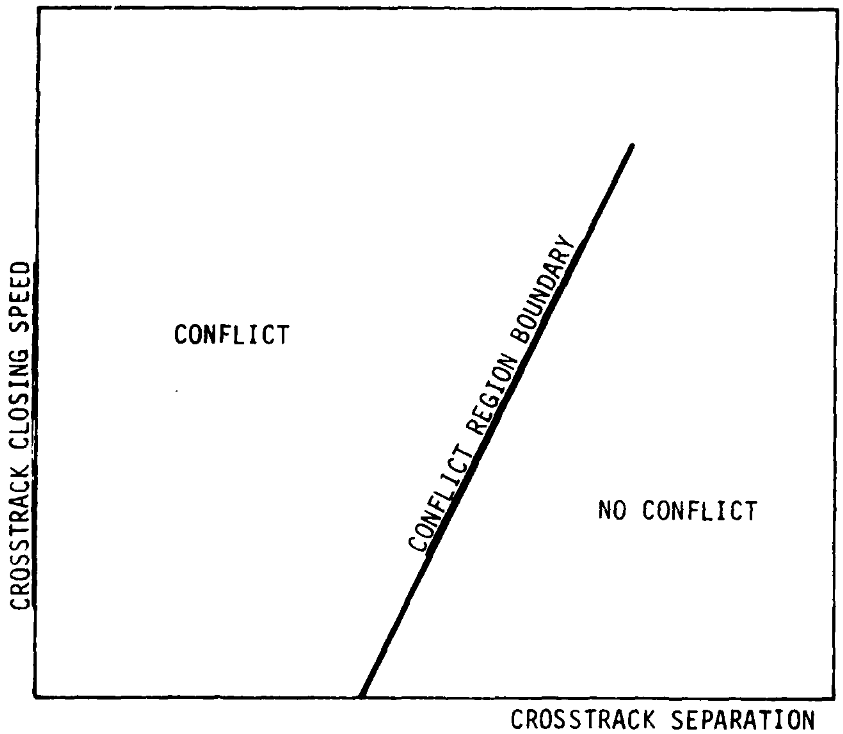
based on one detection rather than two out of the last three. This means that there is only one set of filter factors. In particular our analysis has the Coflict Alert looking ahead 2 minutes and checking for projected separations of less than 5 nmi. The basic impact of these assumptions about the NAS Conflict Alert is that the aircraft pair could be detected somewhat earlier (but not necessarily) in the analysis and thus the analysis might underestimate the risk. The nature of this impact will be investigated in future work.

If the two aircraft are assumed to have the same forward speed then it can be shown that it is possible to approximately determine whether or not an aircraft pair is in conflict from the pair's crosstrack and alongtrack separation and its crosstrack closing speed (see Appendix A of Volume II of this report). Figure 3-2 shows an example of a conflict region for a specific alongtrack separation of the aircraft. In this figure the region to the left of the sloping straight line is the conflict region. It extends from a crosstrack closing speed of zero to the maximum closing speed. The sloping straight line is called the conflict region boundary. For each different alongtrack separation between the aircraft pair there would be a different conflict region boundary. The slope of the boundary would be the same but the intercept with the crosstrack separation axis would change with the alongtrack separation. For example: at an alongtrack separation of zero nmi the conflict boundary intercept is 5 nmi; at an alongtrack separation of 5 nmi the conflict boundary intercept would be 0 nmi. Beyond the alongtrack separation of 5 nmi there would be no conflict region.

3.1.2 Detection, Delay, and Resolution

Because of errors in radar surveillance aircraft position estimates and the smoothing characteristics of the radar tracking algorithm, an aircraft pair might actually be within the conflict region while the output of the tracker reports the pair to be outside the conflict region. This phenomenon will allow aircraft pairs to penetrate the conflict region and lose some separation before the controller realizes the pair is in the conflict region.

To analyze this phenomenon it is assumed that once an aircraft pair has crossed the conflict region boundary, each aircraft will continue to fly in a straight line until told by the controller to do otherwise. The conflict resolution scenario is depicted in Figure 3-3. The figure shows two aircraft nominally



CONFLICT REGION DEFINED FOR A GIVEN ALONGTRACK SEPARATION ASSUMING AIRCRAFT HAVE SAME FORWARD SPEED.

FIGURE 3-2
CONFLICT REGION DIAGRAM

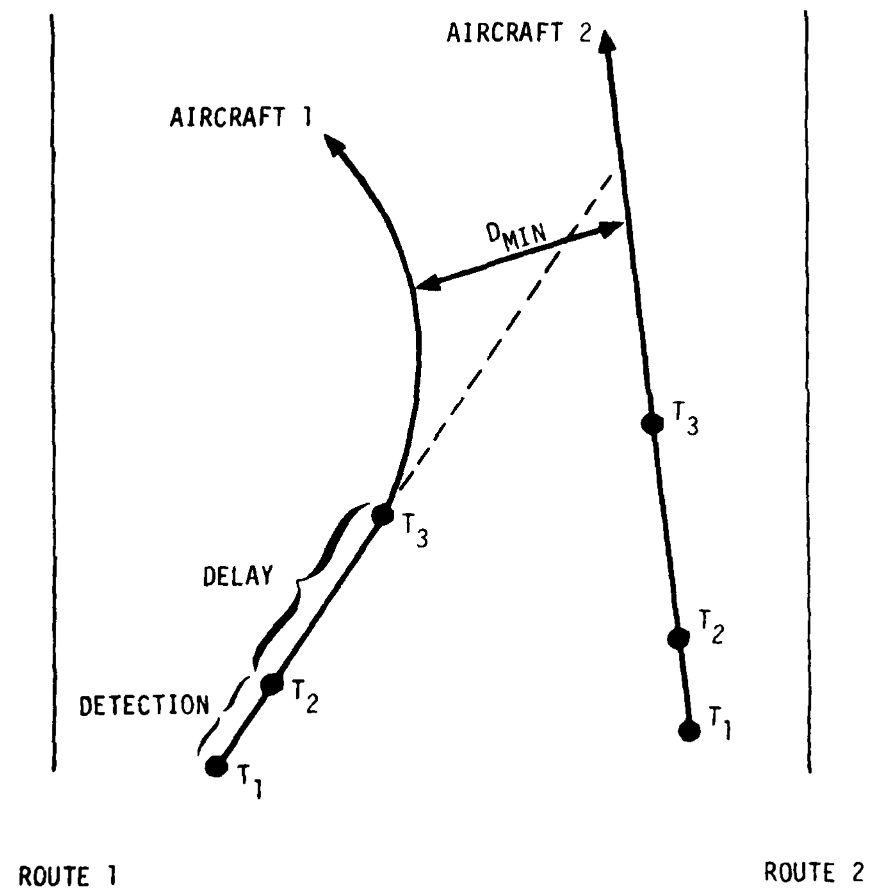


FIGURE 3-3
DETECTION, DELAY, AND RESOLUTION SCENARIO

flying the same direction along two parallel routes. At time T_1 the aircraft are actually on the conflict region boundary. This means that their current spacing and component velocities are such that the pair is projected to be within 5 nmi within 2 minutes. However, the conflict alert function does not detect the pair to be in potential conflict until time T_2. This is due to errors in the estimates of aircraft position and velocity. After the potential conflict is detected there could be a delay until the conflict resolution maneuver starts. This delay could be due to controller workload, communications delay, and pilot reaction time.

It is assumed that the action taken to resolve the conflict is for one aircraft to perform a horizontal turn back toward its assigned route. The assumption of this resolution action in the high altitude airspace leads to a conservative estimate of the probability of horizontal overlap. For the performance envelopes of the aircraft in the high altitude airspace, it is much more likely for an aircraft to resolve a conflict by performing a vertical maneuver to gain altitude separation than to execute a horizontal turn. (11)

The nonmaneuvering aircraft is assumed to fly in a straight line during the time of the collision avoidance maneuver of the other aircraft. This is also a conservative assumption since additional ATC commands could be made and both aircraft could participate in the resolution maneuver. At some point the aircraft will reach a minimum separation and then begin to increase their separation. Figure 3-3 shows one such minimum separation (D_{min}).

In the Conflict Monitoring Analysis the detection, delay, and resolution times are considered to be random variables. The length of the detection time will depend on the errors in the radar returns and on the tracker design. The delay could be very short or very long depending on the reaction times of the controller and the pilot. The resolution maneuver depends on the turn rate chosen by the pilot. The total delay and the turn rate are discussed more fully in Appendix B of volume II of this report.

For a given initial position on the conflict region boundary, a horizontal overlap results from specific combinations of detection time, delay time, and turn rate. A horizontal overlap is defined to occur (given the pair of aircraft is in vertical overlap) when the centers of the aircraft are within a horizontal distance of 2R. The next section will describe how the probability of horizontal overlap is computed.

3.2 The Probability of Horizontal Overlap

This section will briefly outline the computation of the probability of horizontal overlap, P_H. Appendix B of Volume II of this report more fully describes the details of this computation.

The only aircraft pairs which will overlap in the horizontal plane are those that have penetrated the conflict region which was described in the previous section. Of those aircraft pairs that are on the conflict region boundary, only a small fraction will actually come within a distance 2R horizontally. Some aircraft pairs would not enter into horizontal overlap even without controller intervention since the criteria for the conflict alert is predicted closure to within five nmi. Other pairs will not overlap because their avoidance maneuver will remove them from the overlap condition.

To find the probability that pairs do overlap we first consider those aircraft pairs that are on, or very near to, the conflict region boundary. Recall from Section 3.1.1 that the conflict region boundary is defined by specific values of an aircraft pair's crosstrack separation, y, alongtrack separation, x, and its crosstrack closing speed, $\dot{y}$. In the x-y-$\dot{y}$ space we can depict a portion of the conflict region boundary surface as shown in Figure 3-4. In this figure the surface is enclosed in a volume which is Δx by Δy by $\Delta\dot{y}$. A probability is associated with cell i that reflects the probability that a particular coaltitude aircraft pair will have a crosstrack separation in the interval $y_i \pm \Delta y/2$, an alongtrack separation in the interval $x_i \pm \Delta x/2$, and a crosstrack closing speed in the interval $\dot{y}_i \pm \Delta\dot{y}/2$. The dimensions of the cell correspond to the granularity of the data from which the probability is computed, and the range of i corresponds to the range of values x,y, and $\dot{y}$ of the data.

An aircraft pair with x,y, and $\dot{y}$ in cell i could enter into a horizontal overlap situation if it had a particular delay time and turn rate. For an aircraft pair in cell i, an example of the region of delay-turn rate space which will cover the horizontal overlap situations is shown in Figure 3-5. As shown in this figure, if the delay is greater than some value, A, there will be horizontal overlap, regardless of the turn rate of the avoidance maneuver. This is because the delay is so long that the maneuver cannot correct the problem in time to prevent overlap. For delays less than A there could be combinations of values of the turn rate and delay for which there would be

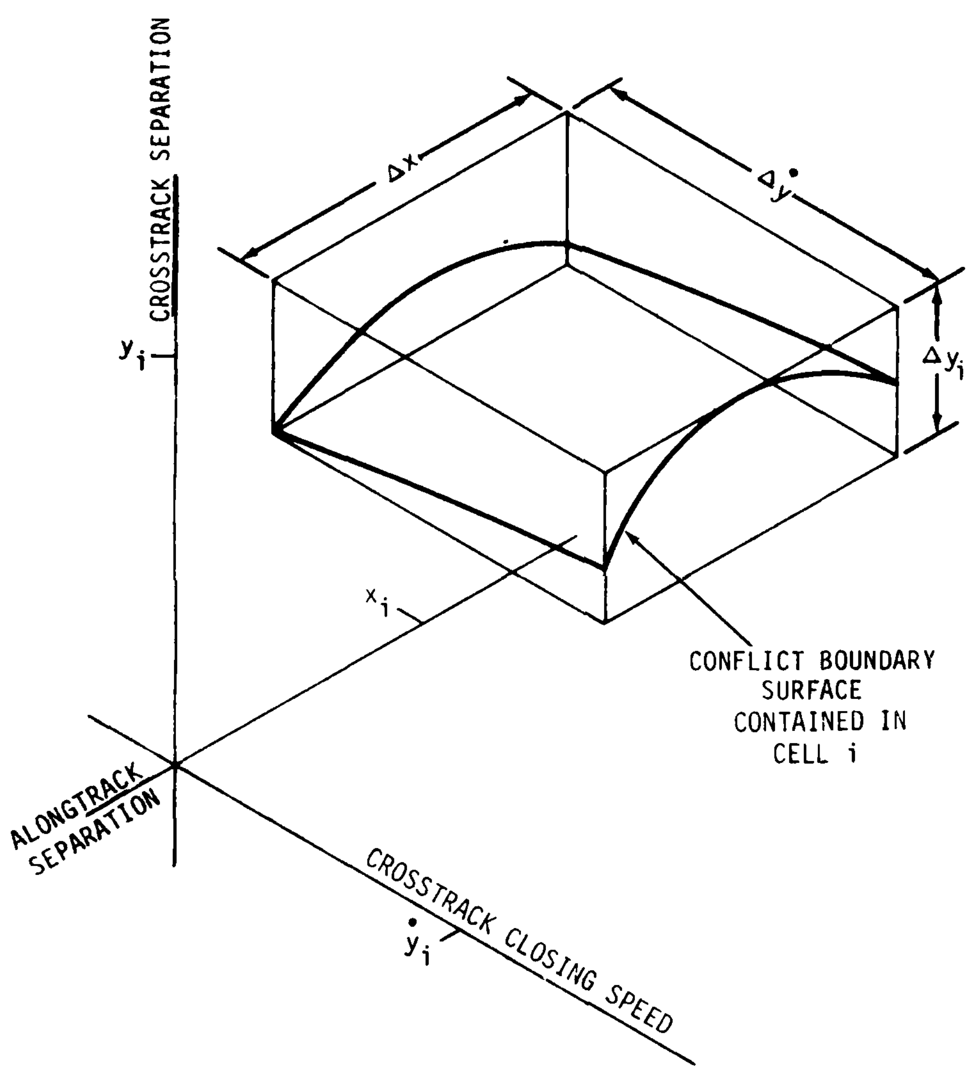


FIGURE 3-4
CONFLICT BOUNDARY SURFACE

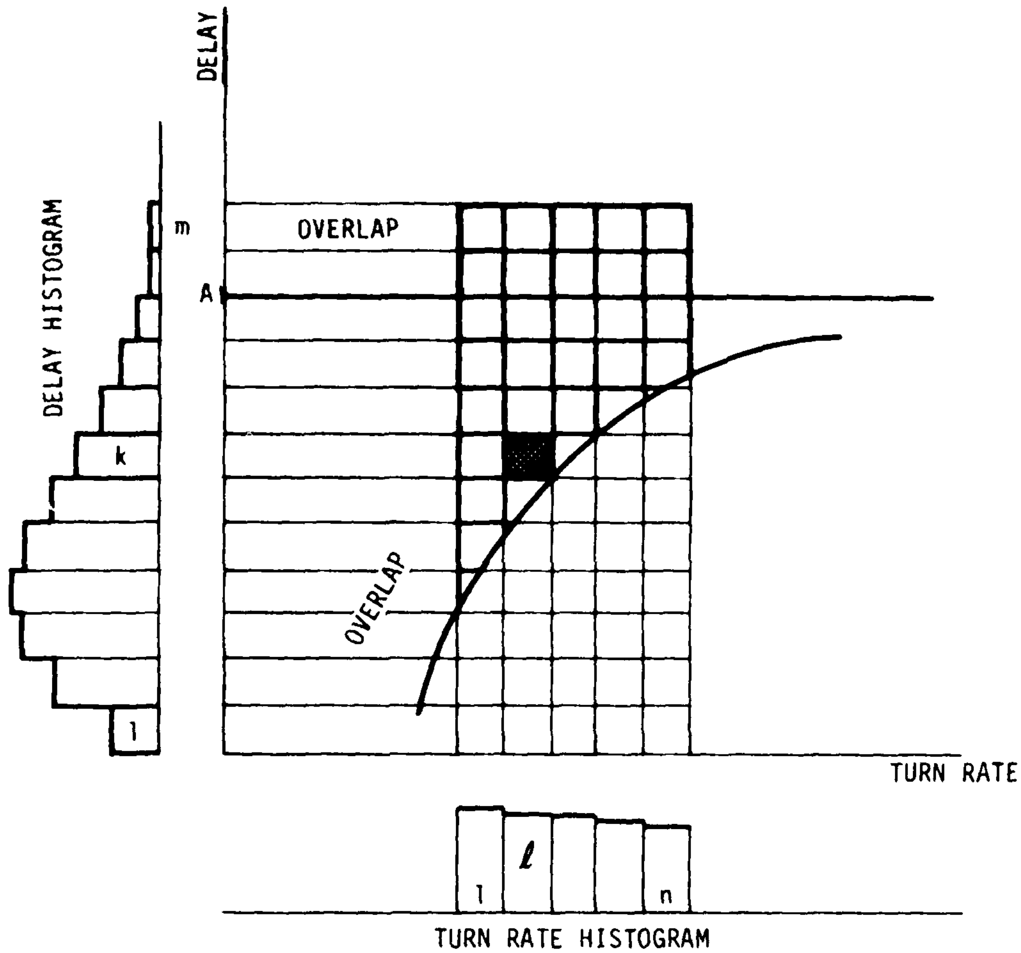


FIGURE 3-5
HORIZONTAL OVERLAP REGION
FOR CONFLICT BOUNDARY CELL i

horizontal overlap. This is represented by the region to the left of the curved line. To the right of this region the delays are short enough and the turn rates are fast enough that there is no overlap.

It should be pointed out that not every conflict boundary cell produces a horizontal overlap region as shown in Figure 3-5. For some cells there may not be any possibility of horizontal overlap. In other cases there is horizontal overlap only after a given length of delay. The detailed development of all the possibilities can be found in Appendix B of volume II of this report.

To compute the probability of horizontal overlap one first computes the probability of horizontal overlap given the aircraft pair is in cell i on the conflict boundary. Referring again to Figure 3-5 we have both the histogram of the total delay and the histogram for the turn rate. Thus the probability of being in the shaded cell in Figure 3-5 is the product of the delay being in cell K and the turn rate being in cell L. The delay and turn rate are assumed to be independent. By summing over all cells enclosed in the horizontal overlap region we arrive at the probability of horizontal overlap given an aircraft pair on the conflict boundary in cell i, $(P(HO|CB_i))$. Therefore, the probability of horizontal overlap, P_H is given by

$$P_H = \sum_i P\left(HO|CB_i\right) * P\left(CB_i\right) \qquad (3\text{-}2)$$

In computing the probability of being in conflict boundary cell i, $P(CB_i)$, we refer back to Figure 3-4. As seen from the figure

$$\begin{aligned} P(CB_i) = P(&y_i - \Delta y/2 < y < y_i + \Delta y/2,\ \dot{y}_i - \Delta\dot{y}/2 < \dot{y} < \dot{y}_i + \Delta\dot{y}/2) \\ &* P(x_i - \Delta x/2 < x < x_i + \Delta x/2) \end{aligned} \qquad (3\text{-}3)$$

The probability of the aircraft pair having a crosstrack separation $y_i \pm \Delta y/2$ and a crosstrack closing speed of $\dot{y}_i \pm \Delta \dot{y}/2$ is estimated from the convolution of the joint crosstrack deviation, crosstrack velocity histogram derived from the data (see Appendix F of volume II of this report).

It is shown in Appendix E of Volume II of this report that the probability that an aircraft pair has an alongtrack separation in the range $x_i \pm \Delta x/2$, $P(|X-X_i| < \Delta x/2)$, will depend only on the traffic loading on each route and the cell size Δx and not on the value of x_i as long as the alongtrack separation is less than the minimum longitudinal spacing, D, of aircraft assigned to he same route. Hence, we can denote for

$$P_{\Delta x} = P(x_i - \Delta x/2 < x < x_i + \Delta x/2) \qquad (3\text{-}4)$$

for $|x_i| < D - \Delta x/2$.

To reiterate, the probability $P(HO\ CB_i)$ is estimated for each cell i by summing over the delay and turn rate histograms as shown in Figure 3-5. The probability

$$P(|y-y_i| < \Delta y_i/2,\ |\dot{y}-\dot{y}_i| < \Delta\dot{y}/2) \qquad (3\text{-}5)$$

is computed from the data.

At this point we should reflect on what the probability in equation (3-5) *represents*. As stated above it is the probability that an aircraft pair is in a cell of dimension Δy (crosstrack separation) by $\Delta\dot{y}$ (crosstrack closing speed) by Δx (alongtrack separation) on the conflict boundary and is heading into the conflict region. It is also true that there is a probability that the aircraft pair is in the conflict region (i.e., the aircraft pair has already passed over the conflict boundary). An aircraft pair in the conflict region is said to be in an "advanced state of conflict" because it must have entered the conflict region at some previous time.

The implication of aircraft pairs being inside the conflict region is important. For instance, as the route spacing is decreased the probability that an aircraft pair is inside the conflict region will increase. However, in the steady state condition for the closely spaced routes the distribution of crosstrack separations and crosstrack closing speeds would have changed from the distribution for the more widely spaced routes. After enough aircraft pairs receive an alert and execute a resolution maneuver there will not be the same probability of finding aircraft as close to each other. Up to this point in the analysis no consideration has been made concerning the modification of the crosstrack separation and closing speed distribution. In fact, a detailed analysis of such a modification is difficult because of the multitude of possible resolution maneuvers and delay times which happen as a

function of time. To make a conservative assumption concerning the effect of the pairs in an advanced state of conflict, we will translate all the aircraft pairs in an advanced state of conflict to the conflict boundary with unchanged crosstrack closing speed. Thus, in addition to computing the probability in equation (3-5) we will also compute the following probability:

$$P(y < y_i,\ |\dot{y}-\dot{y}_i| < \Delta\dot{y}/2) \qquad (3\text{-}6)$$

This is the probability of a pair of aircraft being inside the conflict boundary and having a crosstrack closing speed in the range $\dot{y}_i - \Delta\dot{y}/2 < \dot{y} < \dot{y}_i + \Delta\dot{y}/2$. Thus, two estimates of the probability of horizontal overlap will be made: one using the probability in equation (3-5) and the other using the probability in equation (3-6).

This section has presented the computational procedures used to estimate the probability of horizontal overlap in a surveillance environment with conflict monitoring. The next section addresses the estimation of the term $P_{\Delta x}$.

3.3 The Probability of Alongtrack Separation, $P_{\Delta x}$

In the previous section the term $P_{\Delta x}$ was factored out of the expression for the probability of horizontal overlap. Appendix E of volume II of this report shows that $P_{\Delta x}$ can indeed be factored out. This section discusses one way in which $P_{\Delta x}$ can be computed.

The probability $P_{\Delta x}$ is related to the probability of alongtrack overlap, P_x. The probability of alongtrack overlap is an expression which appears in the procedural formulation of collision risk (see equation 2-2). If the probability of two aircraft on adjacent routes being separated by $x \pm \Delta x/2$ in the alongtrack dimension is independent of x over a particular range of x's (say $|x| < D - \Delta x/2$) then

$$P_{\Delta x} = \frac{P_x \Delta x}{2\lambda_x} \qquad (3\text{-}7)$$

where

λ_x is the length of the aircraft, and
$\Delta x < 2D$ (D being the minimum radar separation).

The calculation of the probability of alongtrack overlap, P_x, is addressed in Reference (12). That document reported on the analysis of a comparison between the probability of alongtrack overlap as computed from data and as estimated by an analytic model which was developed by the ICAO Review of the General Concept of Separation Panel (RGCSP) (Reference 13). For aircraft that are coaltitude, in level flight, and flying in the same direction the analytic model gives a value of P_x as

$$P_x = \frac{4\lambda_x N_1 N_2}{V\left(N_1+N_2\right)} \tag{3-8}$$

where,

V is the forward velocity of the aircraft,

N_i is the flow rate on route i, and

λ_x is the length of the aircraft.

Equation (3-8) was developed under the assumption that the flow rates N_i are constant during a steady-state period. This model was tested in Reference (12) against data from the FAA's data collection. It was found that for appropriately chosen steady-state periods the model agreed quite well with the data. More discussion on this point can be found in Appendix E of volume II of this report.

4. DESCRIPTION OF THE CONFLICT MONITORING INTERVENTION RATE ANALYSIS

One of the important performance measures of an air traffic control system which uses surveillance is the rate at which the controller will intervene with the aircraft due to the control strategy used. In the analysis presented in this paper the rate at which the Conflict Alert will result in controller interventions is important. The controller intervention rate is important for two reasons. First, it would be difficult for the controller to perform all of his tasks if he had to respond to alerts very often. Second, if there were many alerts and the controllers issued commands to the pilots due to these alerts, the charge might be made that the controllers were assuming the pilot's navigation function. It is therefore desirable to minimize the controller intervention rate due to conflict alerts.

The approach used to estimate the controller intervention rate was a simulation using real aircraft flight data, simulated entry times, and the NAS Conflict Alert function.

4.1 The Simulation Approach

In order to model the NAS Conflict Alert function a simulation was performed. A flow chart of the simulation is shown in Figure 4-1. The simulation used smoothed radar tracks of aircraft observed during the data collection and simulated their entry times and flight along a pair of same direction parallel routes. The routes were approximately 160 nmi long, which equals about 25 minutes flying time when flown in a westbound direction. The aircraft tracks were those of actual aircraft which were observed in the FAA's navigation data collection. The times of entry of aircraft on their respective routes were chosen based on the desired flow rates on the routes. The addition of the entry times to the track data defines the traffic flow in the simulation.

Since the tracks from the FAA's data collection were smoothed to get rid of the radar errors, radar errors had to be added to the track data during the simulation. This was accomplished by choosing a radar site relative to the routes and adding range and azimuth errors to each aircraft position report. The errors that were used were representative of the radar beacon system. The range error was 240 feet (1σ) and the azimuth error was .26 degrees (3 ACP's) (1σ). The errors were assumed to be normally distributed with zero mean.

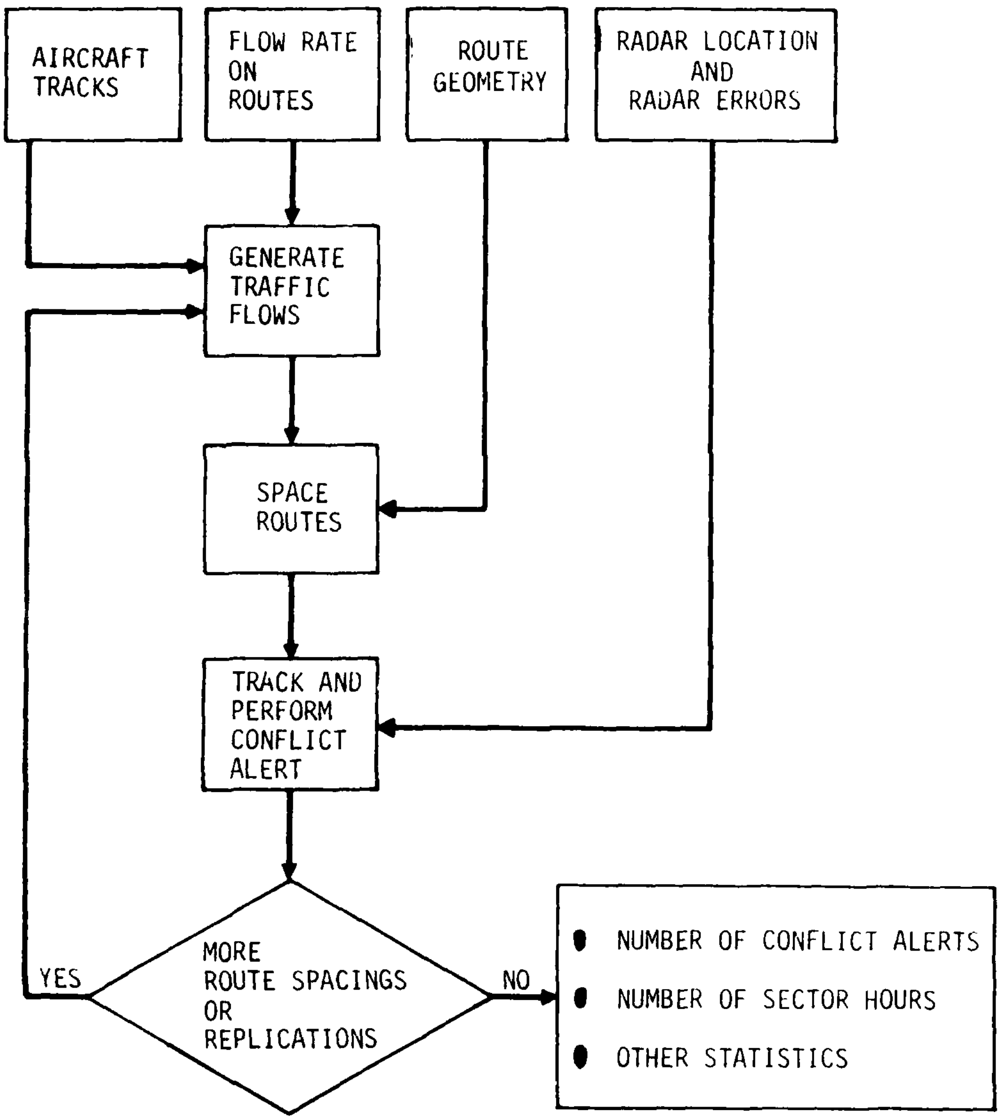


FIGURE 4-1
INTERVENTION RATE SIMULATION

At each radar update time (every 12 seconds), a set of radar returns from every aircraft currently on the routes was processed. This processing included tracking the returns through an emulation of the NAS tracker, and then using the tracker position and velocity estimates in the conflict alert function.

The conflict alert function in the simulation considers only the horizontal plane in determining conflicts. This is in contrast to the NAS Conflict Alert which also considers aircraft transitioning in the vertical plane. In the horizontal plane, the simulation uses the same decision criteria as the NAS Conflict Alert in determining whether a pair of aircraft generate an alert.[14] This includes the two-out-of-three detection logic by which a conflict alert is declared only if the pair of aircraft are detected in potential conflict on two out of the last three filter passes.

When an aircraft pair receives an alert in the simulation, that pair is no longer considered for additional alerts. Furthermore, no attempt is made to realign the tracks of alerted aircraft to account for any response to controller interventions. This means that a given aircraft pair can be detected in conflict only once in the sector of interest. However, the fact that a particular aircraft received an alert with one aircraft did not preclude it from receiving alerts involving other aircraft.

The output from the simulation consists of several statistics. For the controller intervention rate the statistic of interest is the number of conflict alerts per sector hour. Other statistics include the number of hours the simulation was run (sector hours), the number of flying hours in the sector, the number of aircraft generating those flying hours, the maximum instantaneous aircraft count, and the number of conflict alerts declared.

A more detailed description of the simulation is provided in Appendix G of Volume II of this report.

4.2 Limits Imposed on the Horizontal Overlap Analysis by the Intervention Rate

It was mentioned in Section 2.2 that it was assumed that the joint crosstrack separation, crosstrack closing speed histogram would represent time-invariant flying errors. This assumption certainly breaks down if many aircraft pairs get alerts. It is obvious that as an aircraft pair receives an alert, at least

one of the aircraft will change its heading. This will affect both the pair's closing speed and its separation. If enough pairs receive such alerts, then the joint distribution of crosstrack separation and closing speeds will be changed also.

The parameters used in the analysis which most directly influence the controller intervention rate are the route spacing and the flow rates on the routes. Thus, for high flow rates on closely spaced routes, the controller intervention rate is likely to be relatively high. In previous work on an analogous controller intervention rate (Reference 15) it was stated that if more than, say, 10% of the aircraft were affected then the assumption on the stationarity of the underlying joint histogram should be questioned. This point will be discussed again in the results section.

5. TRIAL RESULTS

As a part of the FAA's VOR-defined air route separation program there was a requirement to produce a set of trial results. These trial results were produced in order to allow an evaluation of the applicability of the procedural and conflict monitoring collision risk analyses being performed under the program. Also a comparison could be made between the results of the analyses.

The results in this section are preliminary. There are several issues which need to be resolved before confidence in the analysis and the use of the results can be justified. These issues will be discussed in the recommendations section.

Section 5.1 will first address the results from the conflict monitoring probability of horizontal overlap analysis. The parameter choices and data which were entered into the analysis will be identified in Section 5.1.1. Then the results from both the conflict monitoring and the procedural analyses will be presented in Section 5.1.2. This will be followed in Section 5.2 by the results from the conflict monitoring intervention rate analysis.

5.1 Probability of Horizontal Overlap Results

5.1.1 Inputs

The parameters and data that drive the conflict monitoring horizontal overlap analysis are listed in Table 5-1. Where data were used the data were from observed flights in the Cleveland ARTCC since these were the only data which were available at the time. In most other cases the input is either derived from data or a value was chosen which was based on ancillary simulations or judgment. The choice of parameters such as the aircraft size and velocity, and the characteristics of the delay and bank angle distributions used here may differ from the values eventually selected by the FAA to be representative of the system in general. The following discussion will highlight the inputs and their values.

The crosstrack deviation and crosstrack velocity come directly from the data that was collected during the VOR-defined air route separation program. The form of this data is a joint histogram of the crosstrack deviations and crosstrack speeds for single aircraft. This histogram is convolved with itself as described in Appendix F of olume II of this report to arrive at a joint histogram of crosstrack separation and crosstrack

TABLE 5-1

INPUT TO PROBABILITY OF HORIZONTAL OVERLAP ANALYSIS

INPUT	VALUE	COMMONALITY WITH PROCEDURAL ANALYSIS
Crosstrack Deviations and Speed	-	Yes
Look-Ahead Time	2 Min	No
Minimal Allowable Radar Separation	5 Nmi	No
Radar Update Rate	1 per 12 Sec	No
Radar Beacon		
Range Quantization	0.125 Nmi	No
Azimuth Error	3 ACP's (1σ)	No
Detection Prob.	.95	No
Radar/Tracker		
Separation Error	.7 Nmi (1σ)	No
Closing Speed Error	160 Kts (1σ)	No
Correlation Coef.	-.8	No
Aircraft Size	R = 0.126 Nmi λ_x = 153 Feet λ_y = 108 Feet λ_z = 34 Feet	Yes
Aircraft Velocity	390 Kts	Yes
Flow Rate on Route	.5,5 ac/hr	Yes
Delay Distribution	Gamma C=2 B=6.17	No
Bank Angle Distribution	Uniform 10-30 Degs	No
Route Spacing	8,12,16,20 Nmi	Yes

closing speeds. The joint histogram which was used here was based on aircraft at a distance of 50 nmi from the VOR in the Cleveland ARTCC. The procedural analysis uses the marginal distribution of the crosstrack separation.

The look-ahead time and minimum allowable radar separation are two parameters of the conflict alert function. Even though the NAS Conflict Alert has more parameters (as discussed in the following section on the intervention rate model), the essence of the conflict detection logic is embodied in these two. The nominal values for these parameters are 2 minutes for the look-ahead time and 5 nmi for minimum allowable radar separation.

The radar parameters include the update rate and the radar/tracker errors in position and velocity. The radar update rate for the current en route radars is once every 10 or 12 seconds. A 12 second scan time was chosen for use in this analysis. The radar/tracker errors were arrived at through the simulation described in Appendix C of Volume II of this report. This simulation used as an input the radar range and azimuth errors and the probability of detecting a return on a given scan. The radar beacon errors listed in Table 5-1 are the values usually used as design parameters for the current system. The output of the simulation was a distribution of position and velocity errors. The input to the analysis is summarized in Table 5-1.

There are two elements of conservation placed in the analysis at this point. The first is that the radar/track position and velocity errors are assumed to have a bivariate normal distribution with zero mean and the standard deviations and correlation coefficient from the simulation. This assumption is conservative because the normal distribution has heavier tails than the simulated errors. This means that the bivariate normal distribution will indicate that the aircraft pair is more likely to be observed outside the conflict region when it is really within the conflict region. This will lengthen the detection process as modelled and hence yield probability of horizontal overlap estimates that are higher than those that would result from the direct use of simulated errors.

The second element of conservation is that the flight paths of the aircraft in the simulation were sinusoidal and the radar was looking down the routes. Hence, the resultant radar/tracker errors should be somewhat larger than would be applicable for aircraft which might fly in a more typical manner down the route with a radar located off to the side of the routes.

The aircraft size used in this analysis is representative of a Boeing model 727-200. This aircraft was the one observed most often in the Cleveland center. The aircraft size is given in two ways in Table 5-1. One way is the radius of the right cylindrical collision shape used to compute the probability of horizontal overlap in the surveillance environment. The other way is the width and length of the rectangular collision shape used in the analysis of the probability of horizontal overlap in the procedural environment.

The average aircraft velocity listed in Table 5-1 is the average ground speed of the westbound flights on the routes of interest in the Cleveland ARTCC. There was a spread of observed velocities which depended on both the aircraft type and the winds. However, the average velocity is called for in the analysis.

The flow rate of aircraft on the route determines the alongtrack proximity and overlap in the analysis. The flow rate is ever changing in the system. The objective is to choose a flow rate which is representative of the system. For a given route usage pattern and demand there will be aircraft which are proximate to or will pass aircraft on the adjacent route. The time in proximity or alongtrack overlap from data has been compared to the results of an analytic model in Appendix E of Volume II of this report. The results for a particular set of data indicate that an effective flow rate of about one aircraft every two hours on each route (at a single flight level) gives an equivalent exposure to that found in the data. However, the data had been censored because only those aircraft which actually flew the entire route segment were retained in the data base. The actual effective flow rate would be greater than 0.5 aircraft per hour. A flow rate one order of magnitude greater (5 ac/hr) was also chosen to indicate the sensitivity of the model to this parameter.

The delay and bank angle distributions are unique to the conflict monitoring analysis because they provide the characterization of the collision avoidance maneuver. The delay distribution is based on a British simulation where controllers monitored a threshold line at a given distance from the route centerline.[16] The controllers had computer assistance in determining aircraft transgressions of the threshold line and the delay represented the reaction time for the controllers to send the message to the pilot but did not include the pilot's response time. The delay time data from this simulation was fit to a special form of a Gamma function. The parameters of this distribution imply a mean delay time of about 12 seconds.

However, the form of the distribution allows for very long (and improbable) delays also (i.e. delays greater than 1 minute 0.06% of the time). The British simulation results and the Gamma function fit are shown in Figure 5-1.

The bank angle distribution was assumed to be uniform with a range from 10 to 30 degrees. The maximum value of the bank angle was set at 30 degrees (corresponding to a 0.5g turn) because of passenger comfort considerations. The turn rate will then depend on the velocity of the aircraft. The turn rate distribution for a velocity of 390 knots is shown in Figure 5-2.

The route spacings which were chosen are in the range of 8 to 20 nmi. This upper end of this range was chosen because the trial data were taken on routes that are spaced between 16 to 20 nmi. apart. The lower end of the range was chosen because the current criteria allows routes to be spaced as close as 8 nmi in general.

5.1.2 Comparison of Results from the Conflict Monitoring and Procedural Analyses

The measure of risk we are using for this analysis is the probability of horizontal overlap. In the conflict monitoring environment this probability is estimated via equation (3-2). In the procedural environment the analogous probability is $P_x P_y$.

The data and parameters listed in the previous section were used to produce the conflict monitoring and procedural probability of horizontal overlap estimates shown in Figure 5-3. As discussed in Section 3.2, there are two estimates made for the probability of horizontal overlap in the surveillance environment. One estimate accounts for the aircraft pairs in an advanced state of conflict while the other estimate does not.

In evaluating Figure 5-3 one should remember that these are trial results. The data is representative of only one distance from the VOR (50 nmi) on only a limited number of routes in one ARTCC. The evaluation of the results in Figure 5-3 should be approached with caution. It should be recalled that these are conservative results. This means that the probability is high that the true probability of horizontal overlap in the system is lower than the results in Figure 5-3 indicate. Since all the curves in Figure 5-3 are conservative estimates one cannot make a definitive comparison between the procedural and the conflict monitoring results.

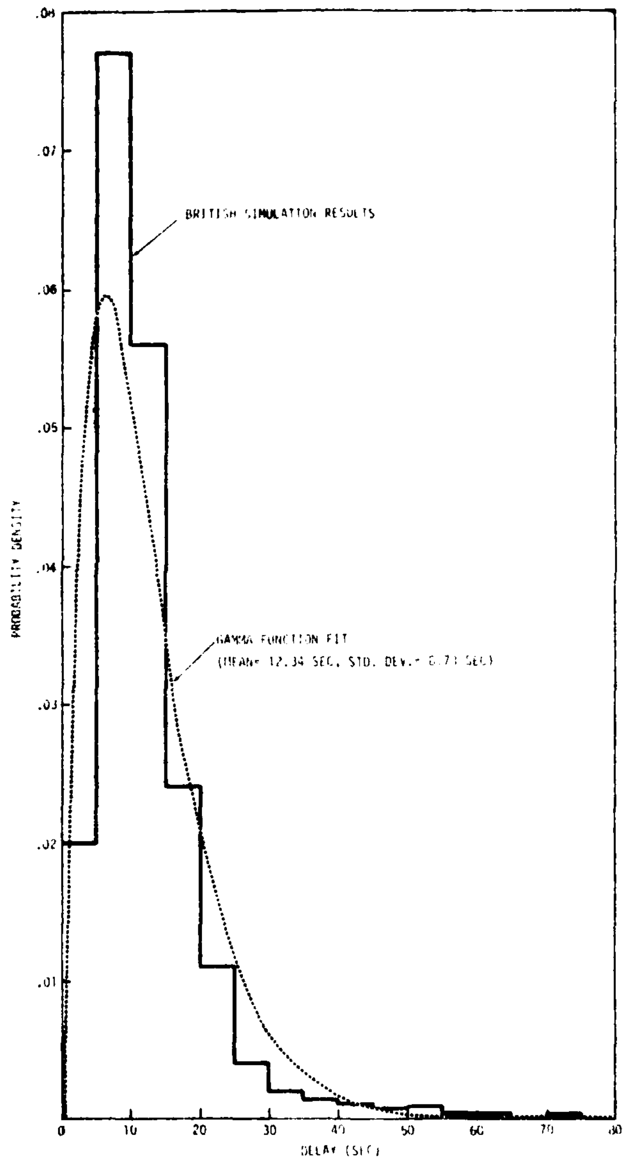


FIGURE 5-1
DELAY DISTRIBUTION

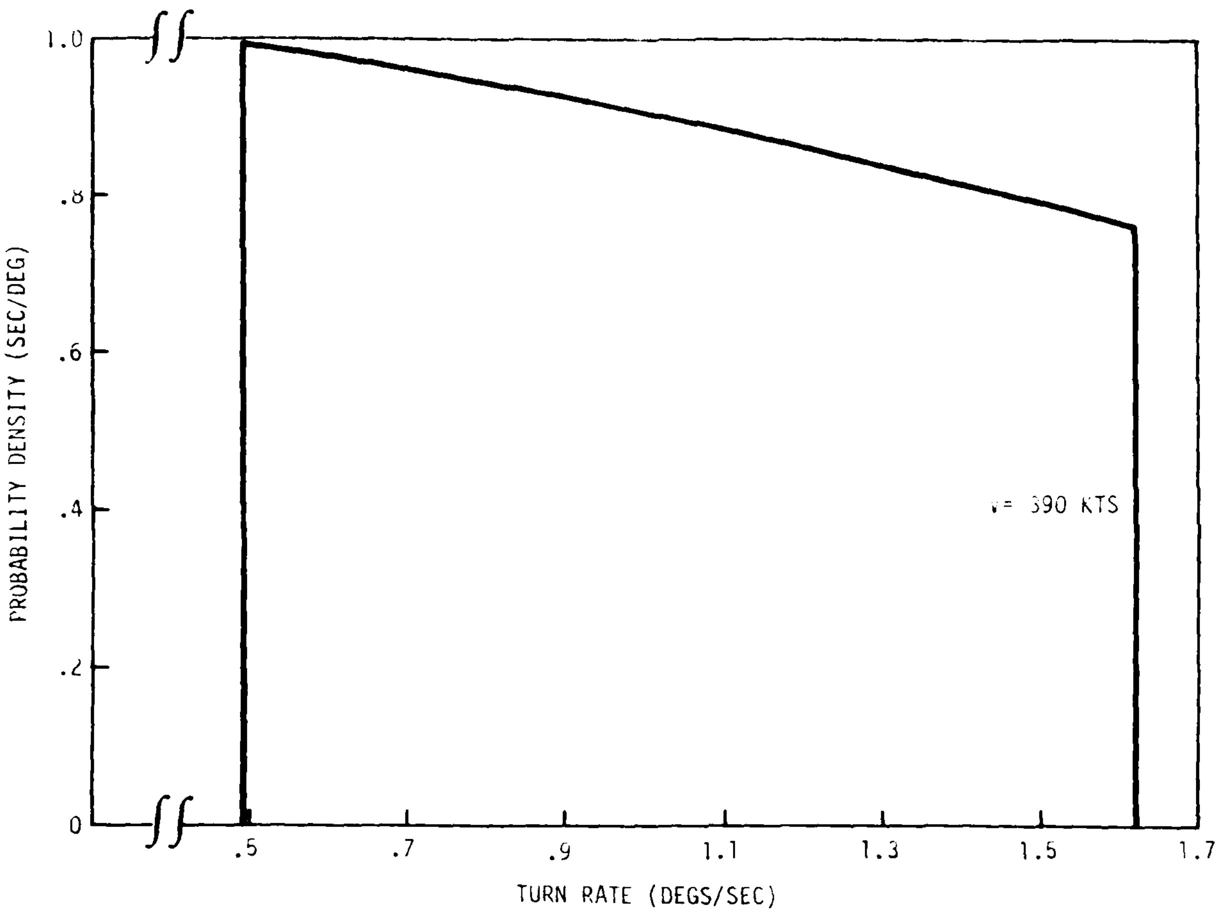


FIGURE 5-2
TURN RATE DISTRIBUTION

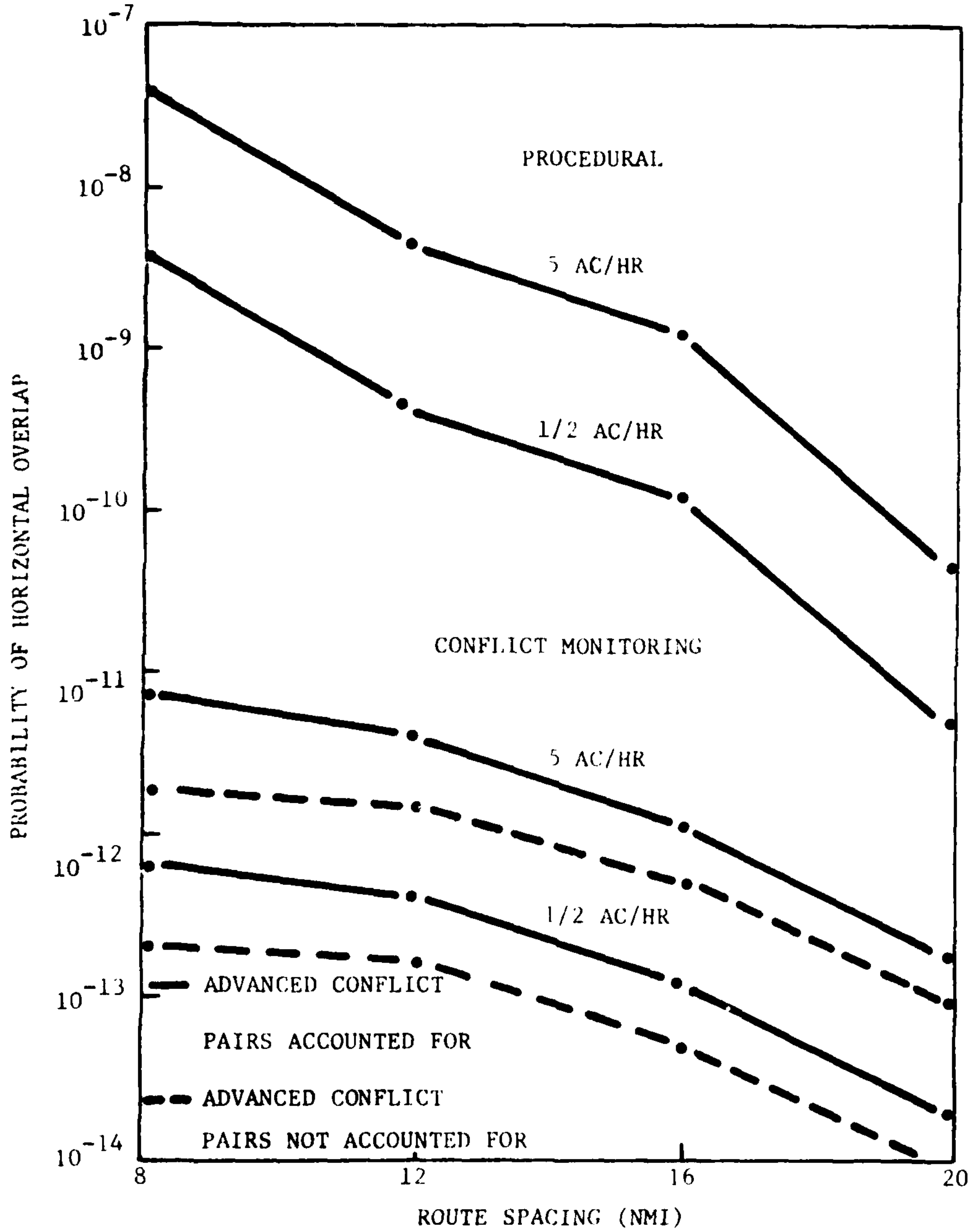


FIGURE 5-3
TRIAL PROBABILITY OF HORIZONTAL OVERLAP ESTIMATES AS A FUNCTION OF ROUTE SPACING

However, one can make the following argument concerning a comparison between the procedural and conflict monitoring results. In the conflict monitoring analysis the same basic assumptions are made concerning the aircraft shape, the independent route loading, and the other features of the analysis which give conservative results. The one conservative assumption that is made in the procedural analysis that is not made in the conflict monitoring analysis is the assumption about collision avoidance not being exercised. When ground-based collision avoidance is included in the conflict monitoring analysis it is included in such a way as to make the probability of horizontal overlap estimates very conservative. For instance, a single horizontal resolution maneuver is assumed for only one aircraft. Also very long delay times and shallow bank angles for the resolution maneuver are included in the analysis. For this reason it is felt that the conflict monitoring estimates for the probability of horizontal overlap are more conservative than the procedural estimates under the same conditions. This means that at least the true probability of horizontal overlap values for each envrionment (procedural or conflict monitoring) should have the same ordinal relationship as indicated by the curves in Figure 5-3.

If one were to use this argument of relative conservatism then a route spacing which is judged to be safe in the procedural environment could be translated to a less widely spaced set of routes via the probability of horizontal overlap corresponding to the procedural result at the safe route spacing.

If, on the other hand, the relative conservatism argument is not used, then one could still make a comparison between the procedural and conflict monitoring results by choosing an acceptable level of the probability of horizontal overlap. If such a level were chosen then it would be obvious which route spacings in the procedural or conflict monitoring environments could be demonstrated to have an acceptable level of horizontal overlap probability. This type of comparison does not depend on the relative conservatism argument but depends only on the conservative aspect of each estimate.

5.2 Intervention Rate Results

The route structure and sector boundaries used in the conflict monitoring intervention rate simulation are shown in Figure 5-4. The basic data which drive the simulation is a set of aircraft tracks from about 200 aircraft. These data are the smoothed radar tracks consisting of an estimated position for each radar

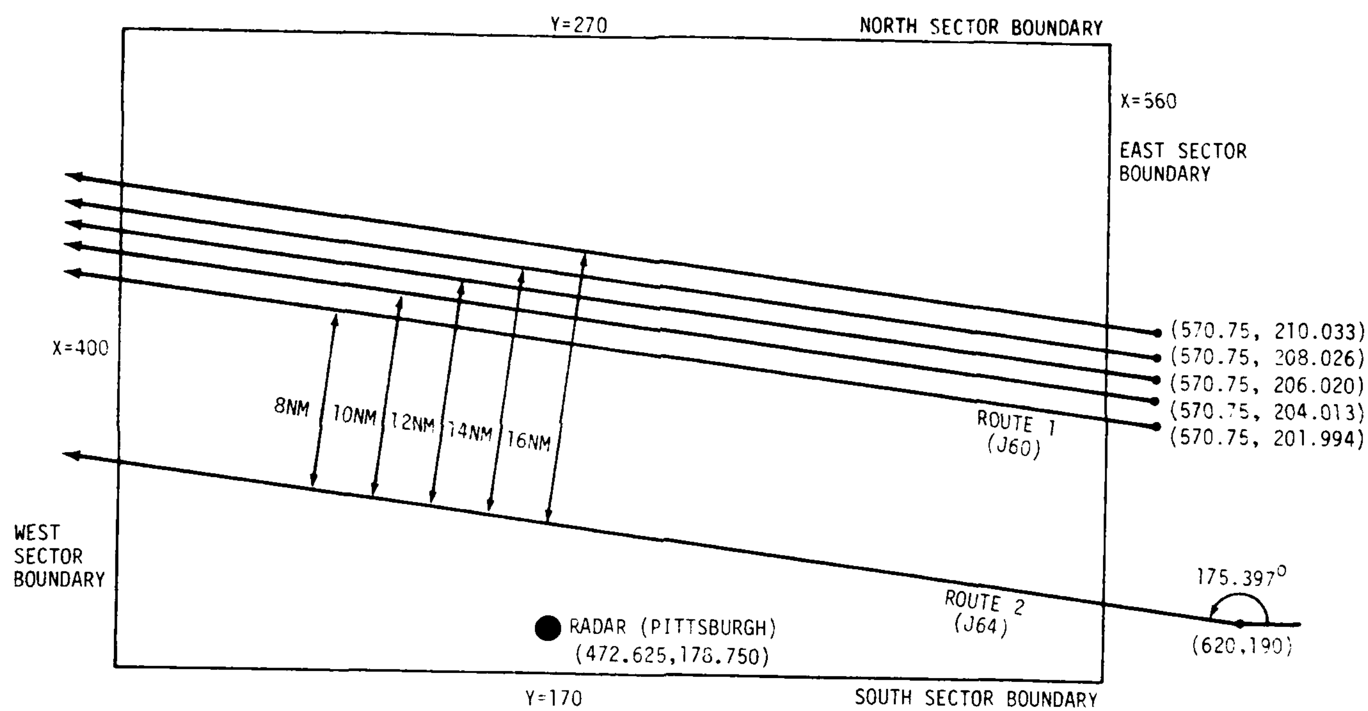


FIGURE 5-4
ROUTE STRUCTURE FOR
INTERVENTION RATE SIMULATION

scan. The tracks are a random sample from the two adjacent westbound routes (J60 and J64) in the Cleveland ARTCC over the entire data collection period. Only those aircraft which flew the entire route segments of interest without controller intervention were eligible to be included in the sample.

In the simulation these aircraft were assigned to the same parallel routes that they flew in the Cleveland ARTCC. The starting points and orientation of the routes are given in Figure 5-4. The conflict alert function in the simulation only operates when the aircraft are in the sector of interest. The sector boundaries are also given in Figure 5-4. All the coordinates are given with respect to an arbitrary ARTCC rectangular coordinate system The position of the radar was chosen to coincide with the Pittsburgh radar. The radar errors and update rate are the same that were used in the horizontal overlap analysis. The simulation duration was chosen to be 4 hours. This includes the starting and ending time for the simulation so that the effective duration is nearer to three hours. The particular parameters for the NAS tracker and the conflict alert function can be found in Appendices C and G of Volume II of this report, respectively. A flow rate of 5 aircraft per hour on each route was assumed.

Ten replications of the simulation were run for each route spacing. The resulting number of conflict alerts for each hour is shown in Table 5-2. This data was fit to a Poisson distribution as shown in Table 5-3. Even though there is not enough data here to perform a statistical test with much power, it nevertheless looks like a respectable fit if the expected number of hours with x conflict alerts is compared with the simulated number of hours with x conflict alerts. If the number of hours with x conflict alerts is Poisson distributed, then a point estimate and a 95% confidence interval can be made for the expected number of conflict alerts per hour based on the data in Table 5-2. The results are shown in Figure 5-5. The results in Figure 5-5 say that based on the output of the simulation our best estimate for the average intervention rate for a particular route spacing is given by the points on the line. Furthermore, based on the output of the simulation we can construct the 95% confidence intervals shown in Figure 5-5 by the brackets. If we were to repeat this simulation many times and construct a 95% confidence interval each time, then under the Poisson assumption 95% of the time the true average intervention rate would be contained in the confidence interval.

TABLE 5-2

INTERVENTION RATE
SIMULATION RESULTS

REPLICATION	HOUR	ROUTE SPACING				
		8	10	12	14	16
1	1	2	0	0	0	
	2	0	0	0	0	0
	3	1	1	0	0	0
2	1	2	2	1	1	0
	2	0	0	0	0	0
3	1	1	1	1	0	0
	2	1	0	0	0	0
	3	0	0	0	0	0
4	1	1	0	0	0	0
	2	1	1	0	0	0
5	1	0	0	0	0	0
	2	0	0	0	0	0
6	1	0	0	0	0	0
	2	0	0	0	0	0
	3	0	0	0	0	0
7	1	0	0	0	0	0
	2	0	0	0	0	0
8	1	1	0	0	0	0
	2	0	0	0	0	0
9	1	1	1	0	0	0
	2	0	0	0	0	0
	3	0	0	0	0	0
10	1	0	0	0	0	0
	2	0	0	0	0	0
TOTALS	24	11	6	2	1	0

TABLE 5-3

POISSON FIT TO SIMULATION DATA

ROUTE SPACING	DATA		POISSON FIT	
	Number of Conflict Alerts (X)	Number of Hours with X Conflict Alerts	Prob of X Conflict Alerts	Expected # of Hours with X Conflict Alerts
8	0	15	.63234	15.2
	1	7	.28982	7.0
	2	2	.06642	1.6
	3	0	.01015	0.2
	4	0	.00116	0.0
10	0	19	.77880	18.7
	1	4	.19470	4.7
	2	1	.02434	0.6
	3	0	.00020	0.0

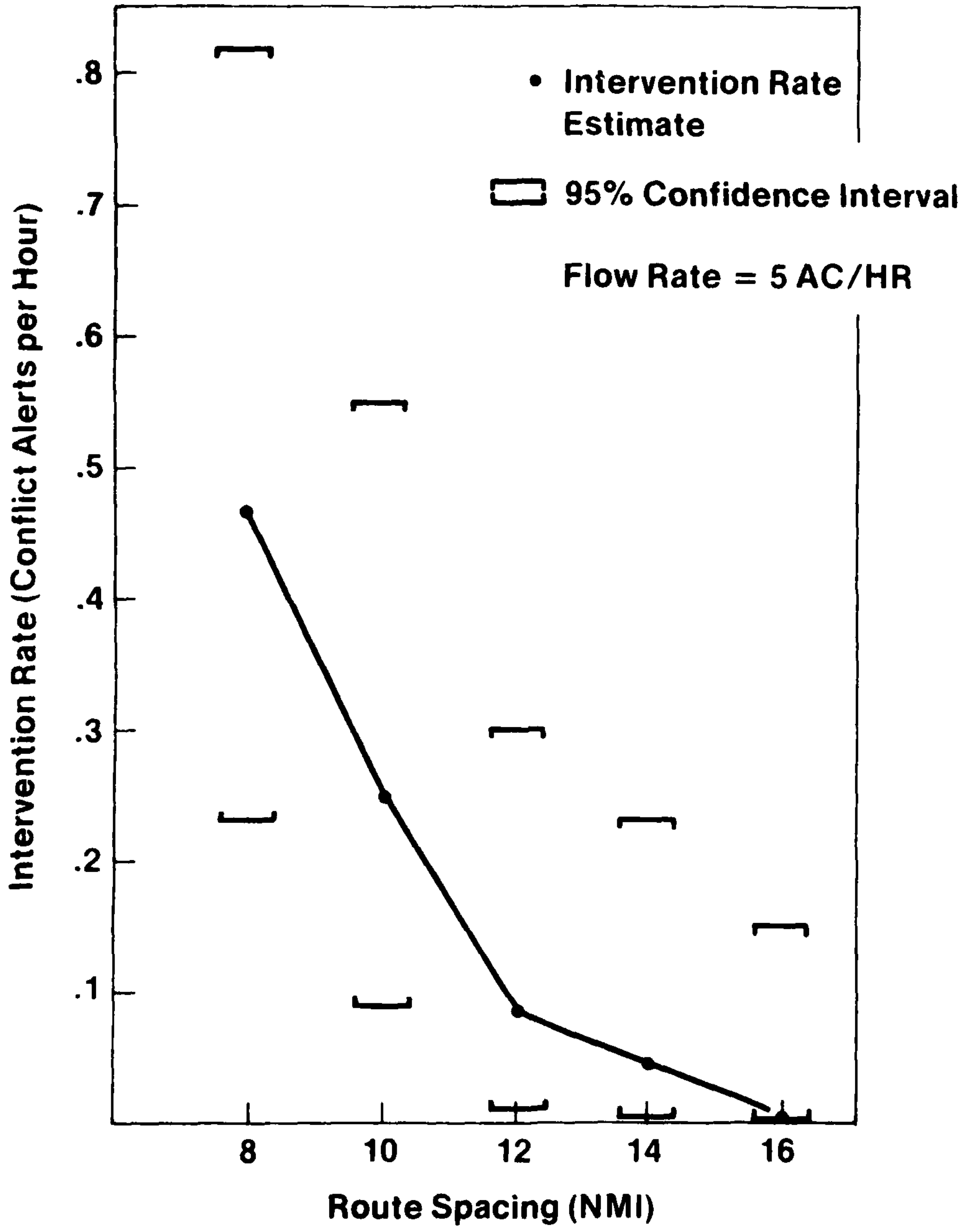


FIGURE 5-5
INTERVENTION RATE
RESULTS FROM SIMULATION

The important result from the simulation is that at a flow rate of 5 aircraft per hour on each route and for a 8 nmi route spacing, the mean intervention rate should be less than one per hour.

As a final result, we present a measure of the limit of the applicability of the analysis. In Section 4.2 it was stated that if the intervention rate were relatively high then the assumption on the stationarity of the underlying joint histogram of the crosstrack separation and the crosstrack closing speed used to estimate the probability of horizontal overlap should be questioned. Besides degrading the overlap estimates there are also other reasons for not wanting high intervention rates. From the controller's point of view a high intervention rate means not only a higher workload but also the possibility that he will treat the conflict alerts as a "nuisance." From the pilot's point of view there may be the feeling that a high controller intervention rate means that the controller is usurping the traditional role of the pilot navigating the aircraft.

A measure of the magnitude of the intervention rate is the percentage of aircraft that receive at least on intervention. If one conflict alert involves two aircraft then two times the number of conflict alerts divided by the total number of aircraft that passed though the sector will estimate the measure proposed above. Table 5-4 shows the number of aircraft seen on both routes during each replication of the simulation and the conflict alerts (CA) that were generated. The percentage of aircraft intervened with is then given for each replication and route spacing. On the average less that 6 1/2% of the flights are involved in a conflict alert. However, for any particular time period (such as time replications 1 through 4 for 8 nmi route spacing) the percentage could be as high as 15%. If we assume that intervening with less than 10% of the aircraft during the time spent in the sector is desirable from both an operational and mathematical viewpoint, then for the data used in the trial estimates it appears that the 5 aircraft per hour flow rate on each route and the 8 nmi route spacing are close to this limit.

TABLE 5-4

PERCENT OF AIRCRAFT
INTERVENED WITH

REPLICATION	NUMBER OF AIRCRAFT	ROUTE SPACING									
		8		10		12		14		16	
		#CA	%	#CA	%	#CA	%	#CA	%	#CA	%
1	41	3	14.6	1	4.9	0	0.0	0	0.0	0	0.0
2	35	2	11.4	2	11.4	1	5.7	1	5.7	0	0.0
3	32	2	12.5	1	6.3	1	6.3	0	0.0	0	0.0
4	34	2	11.8	1	5.9	0	0.0	0	0.0	0	0.0
5	37	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
6	32	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
7	21	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
8	33	1	6.1	0	0.0	0	0.0	0	0.0	0	0.0
9	45	1	4.4	1	4.4	0	0.0	0	0.0	0	0.0
10	40	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
TOTAL	350	11	6.3	6	3.4	2	1.1	1	0.6	0	0.0

6. RECOMMENDATIONS

6.1 Conflict Monitoring Analysis Development

It is recommended that the development of the Conflict Monitoring Analysis be extended to include:

a. A sensitivity analysis which should:

- Investigate the role of the conservative assumptions in both the Conflict Monitoring and the Procedural Analyses. A clearer understanding of the effects of these assumptions would allow a more direct comparison of the results from these two models.

- Investigate the effect of the "imbedded assumptions" in the Conflict Monitoring Analysis. The assumpticn equal speeds of the aircraft is an example of one of the "imbedded assumptions" in the analysis.

- Investigate the sensitivity of the analysis to the parameter values and data. These parameter values include, but are not limited to, the size of the aircraft, the choice of the delay and turn rate distributions, and the navigation and surveillance performance parameters.

b. An augmentation of the analysis. This augmentation should include the consideration of:

- Opposite direction traffic, and

- Transitioning traffic along the route.

6.2 Use of the Analysis

The participants of the FAA's VOR-defined route separation program and the SSRG should come to a consensus on representative values for the parameter values which are used in this type of analysis. Also there needs to be agreement on the method of averaging the probability of horizontal overlap over the length of the route and over the various centers. Additionally, there may be a need to collect data to get an estimate of representative flow rates on the routes. This additional data will be needed to judge the extent to which aircraft were censored from the large data base because they were vectored or did not fly the entire route segment.

If a probability of horizontal overlap measure is to be used in assessing the safety of specific route spacings, then a method of judging the acceptability of this measure should be defined.

6.3 Additional Areas of Investigation

The methodology described above necessarily estimates the average probability of horizontal overlap. It does not consider the overlap for each definable situation which could happen between a pair of aircraft. In order to gain a more direct appreciation of the effectiveness of a surveillance based control system, other measures of system performance should be investigated. These other measures might include the frequency of and risk associated with periods of navigation system or ATC system failure, the frequency of and risk associated with periods of well above average traffic loads on parallel routes, and the risk associated with specific aircraft blunder situations. These considerations would give the decision maker more than one input for the decision process.

If it turns out that for certain traffic densities and for certain route spacings, a surveillance function is required, then the implications of this should be known. It is therefore recommended that the impact on the system of requiring surveillance should be investigated. This investigation should include the question of surveillance/automation system reliability as well as the impact on the controller's procedures.

APPENDIX A

GLOSSARY

ACP	Azimuth Count Pulse. A unit a angular measure equal to 1/4096 of a circle (.0879 degrees).
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
CONUS	Conterminous U.S.. Forty-eight states and the District of Columbia.
D	The minimum radar separation standard
D_{min}	The minimum distance between two aircraft during the resolution maneuver
ICAO	International Civil Aviation Organization
NAS	National Airspace System
NAFEC	The FAA's National Aviation Facilities Experimental Center
P_x, P_y, P_H	The probability of alongtrack (x), crosstrack (y), and horizontal (H) overlap.
$P_{\Delta x}$	The probability that a pair of aircraft is separation by less that an alongtrack distance Δx.
$P(CB_i)$	The probability of an aircraft pair is initially on the conflict boundary in cell i.
$P(HO \mid CB_i)$	The probability of being in horizontal given the aircraft pair was initially on the conflict boundary in cell i.
R	The radius of the aircraft
RGCSP	The Review of the General Concept of Separation Panel.

SSRG	The Radio Technical Commission for Aeronautics' Separation Study Review Group
V	The average velocity of the aircraft
VOR	Very High Frequency Omnidirection Range
x	The alongtrack separation between a pair of aircraft
x_i	A particular alongtrack separation associated with the computational increment i
$\dot{x}$	The alongtrack closing (opening) speed
Δx	The alongtrack separation range of the computational increment
y	The crosstrack separation between a pair of aircraft
$\dot{y}$	The crosstrack closing (opening) speed
y_i	A particular crosstrack separation associated with the computational increment i.
$\dot{y}_i$	A particular crosstrack closing (opening) speed associated with the computational increment i
Δy	The crosstrack separation range of the computational increment.
$\Delta \dot{y}$	The crosstrack closing speed range of the computational increment.

APPENDIX B

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